



Consequences of severe radioactive releases to Nordic Marine environment

Final report for the NKS-B activity 2012

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Consequences of severe radioactive releases to Nordic Marine environment

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Abstract

In the report, consequences of hypothetical severe nuclear accidents releases to Nordic marine environment are preliminary considered. The considered marine area comprises the Baltic Sea (Sweden, Denmark, Finland) and the North Atlantic (Iceland, Faroes, Norway) areas. The hypothetical severe nuclear accidents can be related to nuclear power plants, nuclear powered submarines or ice-breakers.

Quite comprehensive survey on radioactive source terms of extremely severe nuclear power and submarine accidents has been done. This enables to estimate more realistically possible radioactive releases of various elements and nuclides to marine environment. One recent reference is of course the Fukushima accident and estimated releases there.

The marine flows and dilution circumstances around the Nordic nuclear power plants and in the Baltic Sea area in general, has been studied. Respectively marine flows related to Iceland and Faroes coasts are considered with measured data and with preliminary 3D-model simulations. The substantial depth of sea water in the North Atlantic affect vertical concentration profiles to some extent. At Icelandic or Faroese waters, a potential submarine accident would likely occur in a well defined water mass, and radioactivity from the accident would be detected and spread with the flow regime of the water mass in the world ocean.

Based on hypothetical severe accidents scenarios, preliminary consequence calculations has been done. It should be emphasised that the considered severe accident cases, considered in this study, do not directly attach any

specific Nordic nuclear power plant or any specific submarine type. The considered radioactive releases will, however, provide specified references for more extensive consideration of environmental consequences of severe - or minor – radioactive releases to Nordic marine environment.

As a reference, the release amounts from a 3000 MW_{th} reactor size were used. Based on source term analyses, the chosen release fractions in the study were: iodine 20% (of the total core inventory), caesium 10%, tellurium 10%, strontium 0.5%, ruthenium 0.5%. The considered release event to marine environment were assumed to start ten hours after shutdown of the reactor. Total released amounts of the most important nuclides were estimated to be: $4.85 \cdot 10^{17}$ Bq (I-131), $7.29 \cdot 10^{16}$ Bq (Cs-134) and $4.17 \cdot 10^{16}$ Bq (Cs-137).

Due to the highly contaminated sea food, the arising doses to human from a hypothetical severe nuclear power plant accident would be high especially in local sea area. Based on preliminary results, annual individual doses could be ten to some hundreds of millisieverts from local sea area. The most important nuclides were Cs-134, Cs-137 and I-131 causing 96% of the total ingestion dose.

In the Baltic Sea area, the arising doses from a severe nuclear power plant accident assumed to happen e.g. at Gulf of Finland, would be about 1/10000 compared to doses in the local sea area. Thus the arising maximum annual individual dose for fish pathway is in the level of 0.1 mSv in the Baltic Sea area.

Submarine accident assumed to happen at Icelandic waters, has been analysed in the study. The calculated collective dose rates to man as well as doses to a critical group are significantly lower than doses from natural sources. However, in local considerations dose-rates are significantly higher than the negligible component to the annual individual dose obtained from natural sources (UNSCEAR, 2000) and, therefore, have to be taken into consideration during evaluation of the accident consequences.

Key words

severe radioactive releases, marine environment, nuclear power plants, submarines, doses

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COSEMA



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COsequences of SEvere radioactive releases to Nordic MArine environment

Final report for the NKS-B activity 2012

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1 Introduction

In the activity marine input data and preliminary consequences of hypothetical severe nuclear accidents releases to Nordic marine environment are considered. The considered marine area comprises the Baltic Sea (Sweden, Denmark, Finland) and the North Atlantic (Iceland, Faroe Islands, Norway) areas. The hypothetical severe nuclear accidents can be related to nuclear power plants (NPP), nuclear powered submarines or ice-breakers.

Quite comprehensive survey on radioactive source terms of extremely severe nuclear power and submarine accidents has been done. This enables to estimate more realistically possible radioactive releases of various elements and nuclides to marine environment. One recent reference is of course the Fukushima accident and estimated releases there.

The marine flows and dilution circumstances around the Nordic nuclear power plants and in the Baltic Sea area in general, has been studied. Respectively marine flows related to Iceland and Faroes coasts are considered with measured data and with preliminary 3D-model simulations. The substantial depth of sea water in the North Atlantic affects vertical concentration profiles to some extent.

The element specific marine transfer data, like sorption factors, has been reviewed. The sorption characteristics of various elements affect their behaviour and distribution between water and suspended solids in sea. Further this sorption factor creates the concentration distributions between sea water and bottom sediment.

Based on hypothetical severe accidents scenarios, preliminary consequence calculations have been done. It should be emphasised that the considered severe accident cases, considered in this study, do not directly attach any specific Nordic nuclear power plant or any specific submarine type. The considered radioactive releases will, however, provide specified references for more extensive consideration of environmental consequences of severe - or minor – radioactive releases to Nordic marine environment.

This report is an interim report of the planned two years research activity.

2 Hypothetical severe nuclear accidents in Nordic marine environment

Around the Baltic Sea there are several nuclear power plant units also in Sweden and in Finland. In Forsmark there are three BWR's (2x2928 MW_{th} and one 3300 MW_{th}). In Ringhals there are four reactors: one BWR (2540 MW_{th}) and three PWR's (2652, 3135 and 2775 MW_{th}). In Oskarshamn there are three BWR's: 1375 MW_{th}, 1800 MW_{th} and 3300 MW_{th}. In Loviisa there are two PWR's (2x1500 MW_{th}) (Lahtinen, J., 2012). A summary of nuclear facilities around the Baltic Sea is presented e.g. in an earlier study (Nielsen, S.P., et al., 2010).

It can be concluded that the greatest thermal reactor power of 3300 MW (corresponds to about 1000 MW_e) represent the highest level of radionuclide inventories which could partially be released from the core in a hypothetical severe accident. This kind of reference accident case, so called worst case accident scenario, does not refer to any specific reactor in Nordic countries, but provides a picture of highest environmental consequences which could appear with very low probability. Consequences of smaller radioactive releases to Nordic marine environment can then quite easily be estimated based on the worst case accident results. Severe nuclear power plant accidents releases and consequences are planned to be considered starting from locations of current nuclear power plants in Finland and Sweden.

A severe nuclear power plant or submarine accident could result e.g. from operational reasons, coolant leakages (LOCA-accidents) or external treats. The radioactive source term from a severe damaged reactor core is in the study mainly assumed to be consisted of soluble substances like caesium and iodine radionuclides. The source term evaluation will be based on an assumption that functioning of all cooling safety systems of the considered reactor has been lost. In this case the reactor core is expected to melt finally significantly, causing large releases of volatile nuclides to the marine environment. The effect of duration of the source term will also be considered, because it is expected that a shorter release will produce elevated seawater and sediment concentrations at the local sea area, near the considered nuclear power plant or a submarine vessel. The released radionuclides will further disperse via marine flows to the whole Baltic Sea area or to the North Atlantic. Despite large dilution, the released radionuclides will cause some collective exposure also in the whole Baltic and North Sea areas.

Nuclear-powered submarine accidents near Iceland or the Faroese coasts might create special threats for the local marine ecology. These untypical radioactive release events in Atlantic are considered in consequence assessments of the activity as well.

References

Lahtinen, J., COSEMA activity working report, 2012.

Nielsen, Sven P., Lüning, M., Ilus, E., Outola, I., Ikäheimonen, T., Mattila, J., Herrman, J., Kanisch, G., Osvath, I., 2010, Baltic Sea, Radionuclides in the Environment, ISBN 978-0-470-71434-8.

3 Marine flows

3.1 Baltic Sea area

M. Isaksson, P. Roos, V. Suolonen

Marine flows around the Forsmark NPP and Ringhals NPP

Modelling of the water movements and ecological impact has been performed for the estuarine area outside the Forsmark power plant. Model estimations by Engqvist & Andrejev (1999) of the water exchange of the area adjacent to the plant as well as for the whole Baltic showed good resemblance with observed circulation.

Kumblad et al. (2006) was able to estimate the concentration of radionuclides in a modelled ecosystem with bioconcentration factors for plants and adsorption coefficients (K_d) as input parameters. The model was based on site-specific carbon dynamics and three radionuclide specific mechanisms: plant uptake, excretion by animals, and adsorption organic surfaces. The model suggest that the water exchange rate in the area is important considering radionuclide exposure to organisms, due to dilution of the water as well as by replacing the plankton with organisms that are not contaminated.

Concerning the vicinity of the Ringhals NPP, Holtegaard Nielsen (2005) presents data for the circulation in the Kattegat. In contrast to the common description that a large part of the area is governed by a basic estuarine circulation, Nielsen found anti-cyclonic circulation in a large part of the upper layer. This circulation was driven by a density gradient at the border between Kattegat and Skagerrak.

Spokes et al. (2006) found that the coastline and the islands within the Kattegat influence the entire Kattegat Sea region. The influence of the land masses gives rise to horizontal gradients in a large number of parameters. Atmospheric transport and deposition must therefore, according to Spokes et al., be modelled using the individual atmospheric conditions.

Marine flows around the Loviisa NPP

Generally, in the Gulf of Finland there is a circulation flow counter-clockwise, following the coasts of Estonia, Russia and Finland (Andrejev, et al., 2004). Thus the salinity of the water is slightly lower at the coastal area of Finland than in the coast of Estonia.

The islands restrict to some extent sea water flow from the Loviisa NPP local sea area Hästholmsfjärden to elsewhere of the Gulf of Finland. About distance of five kilometres from the plant, the areal density of islands decreases and the average depth of the sea is about 30 - 40 meters.

The water exchange rate of the local sea area beside the plant is 57 m³/s in normal operational use mode. Without cooling flow rate of the plant, natural water exchange rate in local sea area is about 28 m³/s. The corresponding water turnover of the local sea is about eight times per year. So the cooling flow rate determines the water exchange rate in normal operational use of the plant.

In this study it is however conservatively assumed that the cooling system is damaged during the release and dispersion phases of radionuclides in a severe nuclear power plant accident event. The effective dilution in local sea area is smaller in the case of natural flow circumstances in the local sea area.

References

Andrejev, O., Myrberg, K., Alenius, P., Lundberg, P. A., 2004. Mean circulation and water exchange in the Gulf of Finland – a study based on three-dimensional modelling, *Boreal Environmental Research*, 9:1-16.

Engqvist, A., Andrejev, O., 1999. Water Exchange of Öregrundsgrepen - A Baroclinic 3D-model Study. Swedish Nuclear Fuel and Waste Management Co., Stockholm, Sweden. SKB TR 99-11.

Holtegaard Nielsen, M., 2005. The baroclinic surface currents in the Kattegat. *Journal of Marine Systems* 55, 97-121.

Kumblad, L., Kautsky, U. & Næslund, B., 2006. Transport and fate of radionuclides in aquatic environments - the use of ecosystem modelling for exposure assessments of nuclear facilities. *Journal of Environmental Radioactivity* 87, 107-129.

Spokes, L., Jickells, T., Weston, K., Gustafsson, B.G., Johnsson, M., Liljebladh, B., Conley, D., Ambelas-Skjødth, C., Brandt, J., Carstensen, J., Christiansen, T., Frohn, L., Geernaert, G., Hertel, O., Jensen, B., Lundsgaard, C., Markager, S., Martinsen, W., Møller, B., Pedersen, B., Sauerberg, K., Sørensen, L.L., Hasager, C.C., Sempreviva, A.M., Pryor, S.C., Lund, S.W., Larsen, S., Tjernström, M., Svensson, G. & Zagar, M., 2006. MEAD: An interdisciplinary study of the marine effects of atmospheric deposition in the Kattegat. *Environmental Pollution* 140, 453-462.

3.2 Faroes

H. P. Joensen

A brief overview of ocean currents and radioactivity around the Faroe Islands is given in this section.

Main currents

Figure 1 gives an overview of the main surface current systems in the North Atlantic and the Nordic Seas (AMAP, 2010; Aure, J. *et. al.*, 1998).

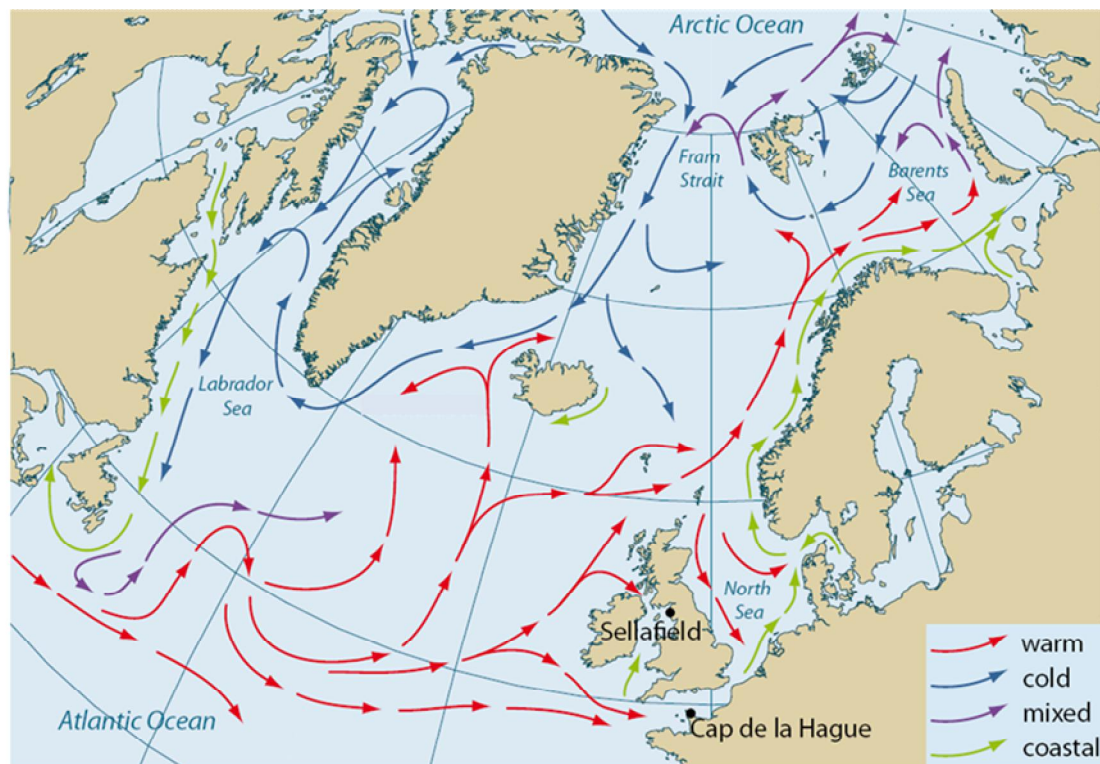


Fig. 1. Overview of main currents in the North Atlantic area (AMAP, 2010; Aure *et. al.*, 1998)

The main currents in the upper layer closer to the Faroe Islands and Iceland are illustrated in Figure 2 (Hansen, 2000). Warm North Atlantic Water (NAS, IS) is flowing northward with branches around the Faroe Islands and Iceland into the Norwegian Sea in the north, where it is cooled down and partly sinks to deeper layers. The main water flux into the Norwegian Sea is between Iceland and Scotland. A slope current is northward along the Scottish and the Norwegian shelf. Cold water (the East Greenland Current, EGS) flows from north southward along East Greenland through the Denmark Strait in the south, and continues westward south of Greenland. A northern branch flows eastward north of Iceland and towards the Faroe Islands (the East Icelandic Current, EIS), where it meets warm Atlantic Water. The Icelandic Front (IF) is found where the

warm Atlantic Water from the south meets colder water from the north. The front separates the two water masses. It is relatively close to the Faroe Islands, and the warm Atlantic Water flow north of the Faroes (the Faroe Current, FS) becomes a narrow eastward flow.

The main pattern of the southward overflow at lower depth from the north across the Greenland-Scotland ridge and into the North Atlantic is shown in Figure 3 and 4. It contains cold water from the deep layers in the north. In the Faroese area, the main overflow occurs in the bottom layer of the Faroe-Shetland channel in the east, between Shetland and the Faroe Islands. The overflow is part of the mass balance system between northward and southward water flow that again is part of the great conveyor belt known in oceanography, i.e. the thermohaline circulation in the world ocean (Fig. 5).

Water masses and radioactivity

Ocean water is characterized by physical and chemical properties as density, temperature and salinity. The world ocean contains large water bodies that can be identified according to their physical and chemical properties. The water bodies are known as "water masses" in oceanography.

Figure 6 illustrate the average water mass distribution around the Faroe Islands. The boundaries between the masses will always be somewhat ambiguous. They have different origins, according to the flow patterns in the open ocean, and this needs to be considered in the case of e.g. a submarine accident. A potential submarine accident would likely occur in a well defined water mass, and radioactivity from the accident would be detected and spread with the flow regime of the water mass in the world ocean.

Vertical profiles of Cs-137 and Sr-90 have been taken around the Faroe Islands. Results from a survey in August 1990 at a station north of the islands (Fig. 7) are shown in Figure 8, together with the ratio between the activity concentrations (Dahlgaard *et al.*, 1991). The position is at 63°N20'N6°05'W, where the bottom depth is 2400m. The origin of the samples as related to water mass specification was determined from hydrographical analyses. A notable maximum is observed in the profiles at 400m. The ratios indicate input of the isotopes from other sources than global fallout. The range of the isotope ratio is 2.1-3.0, and Dahlgaard *et al.* conclude that it corresponds to increased input from Sellafield/Chernobyl, and that the peak at 400m depth as based on results from their hydrographical measurements corresponds to input of seawater from the Greenland Sea (cf. Fig.4). The lowest ratio of 2.1 at 1000m may still be considered relatively high compared to the fallout ratio of about 1.5, as this water had not recently been in contact with the atmosphere.

Long term time series of radioactivity in Faroese waters are shown in Figures 9 and 10 (AMAP, 2010), together with measurements from off the west and east coasts of Greenland. The activity concentrations are generally observed to be lower off the Faroe Islands than off the Greenland coasts. A signal from the Chernobyl accident can be seen in the Faroese data set.

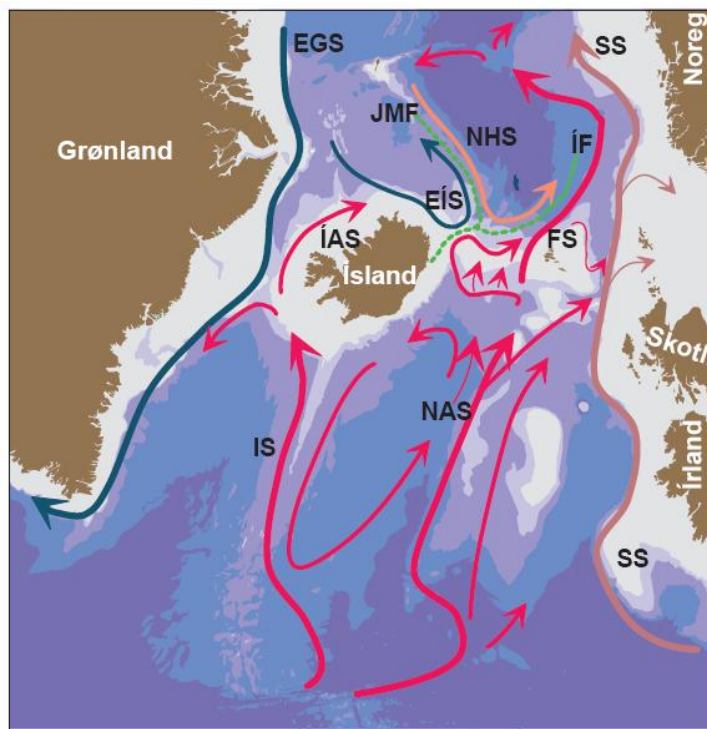


Fig. 2. Upper layer water flows. (Hansen, 2000).

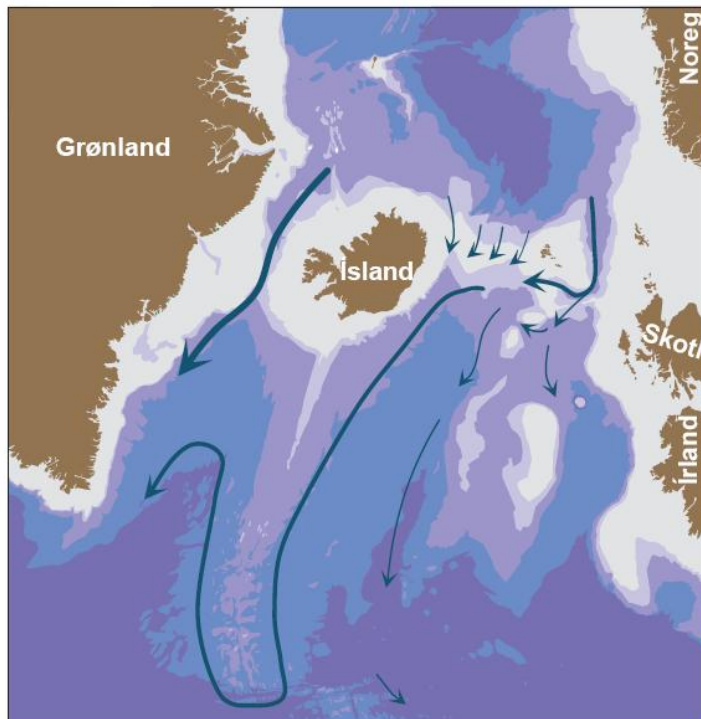


Fig. 3. Main pattern of overflow water. (Hansen, 2000).



Fig. 4. Cold southward flow over the Greenland-Iceland-Scotland ridge. The blue area illustrates the depth below 1000m (Hansen, 2000).

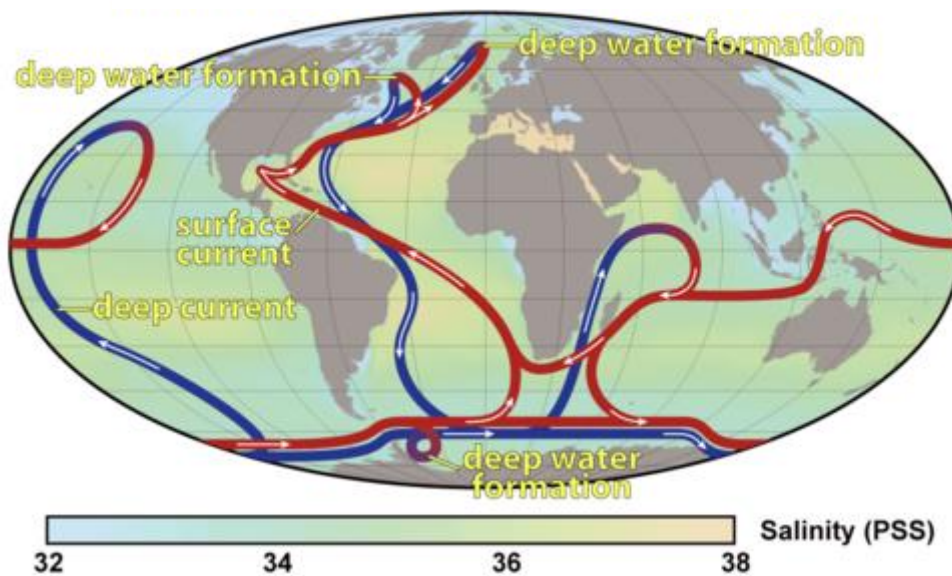


Fig. 5. The conveyor belt showing the thermohaline circulation in the world ocean (picture from internet).

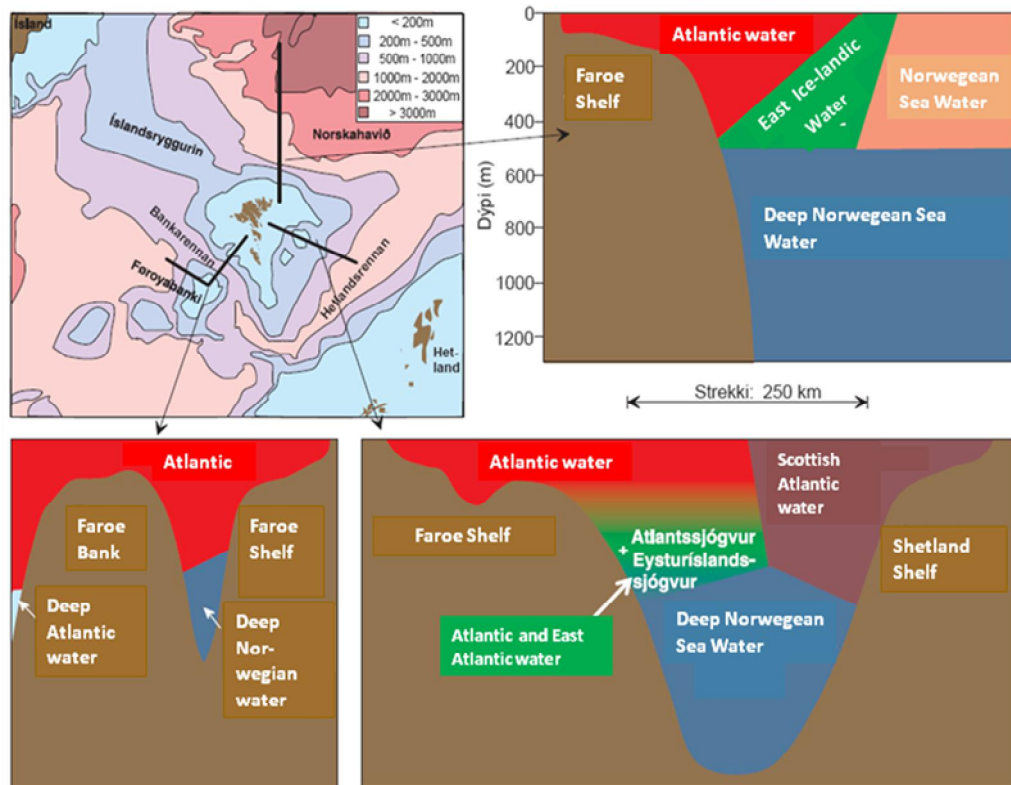


Fig. 6. Usual water mass distribution. (Hansen, 2000).

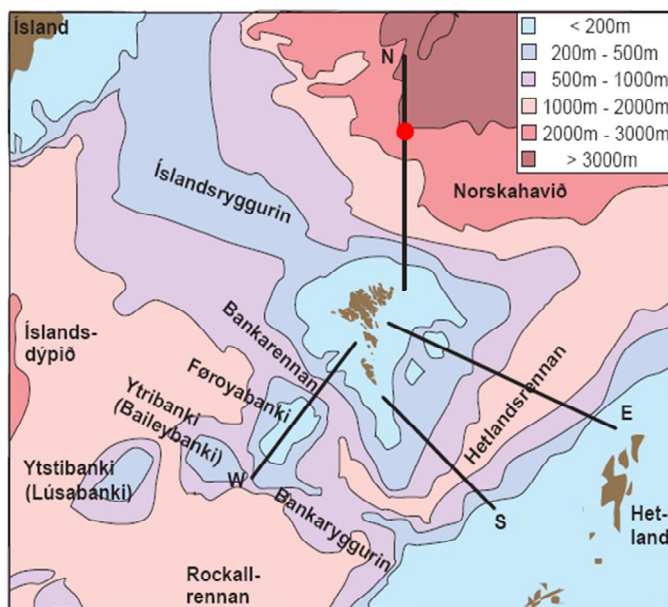


Fig. 7. Bottom topography. Depth profiles were taken at the station marked with the red dot.

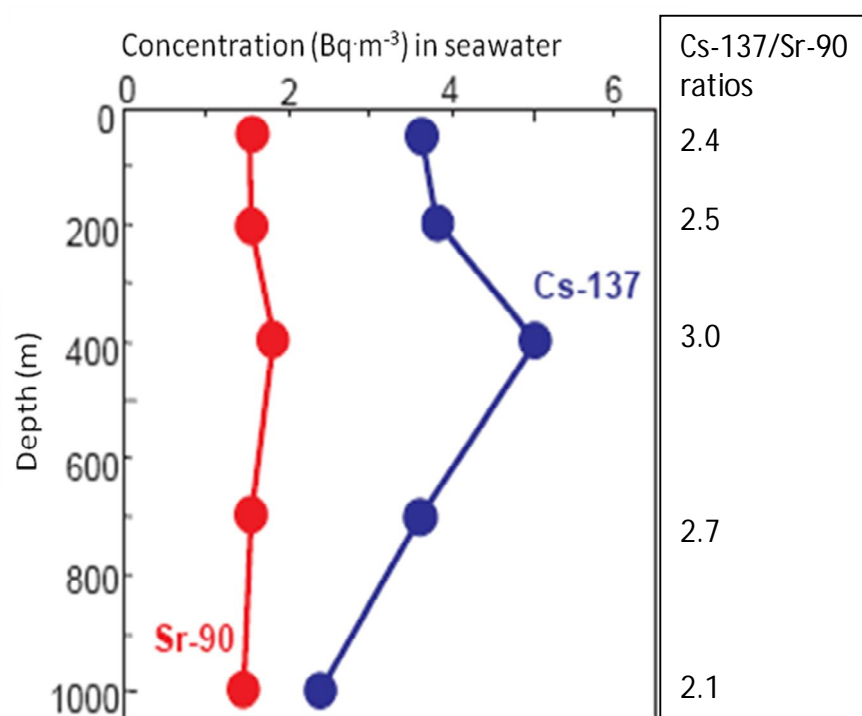


Fig. 8. Profiles of Cs-137 and Sr-90 north of the Faroes in August 1990(cf. Fig. 6).

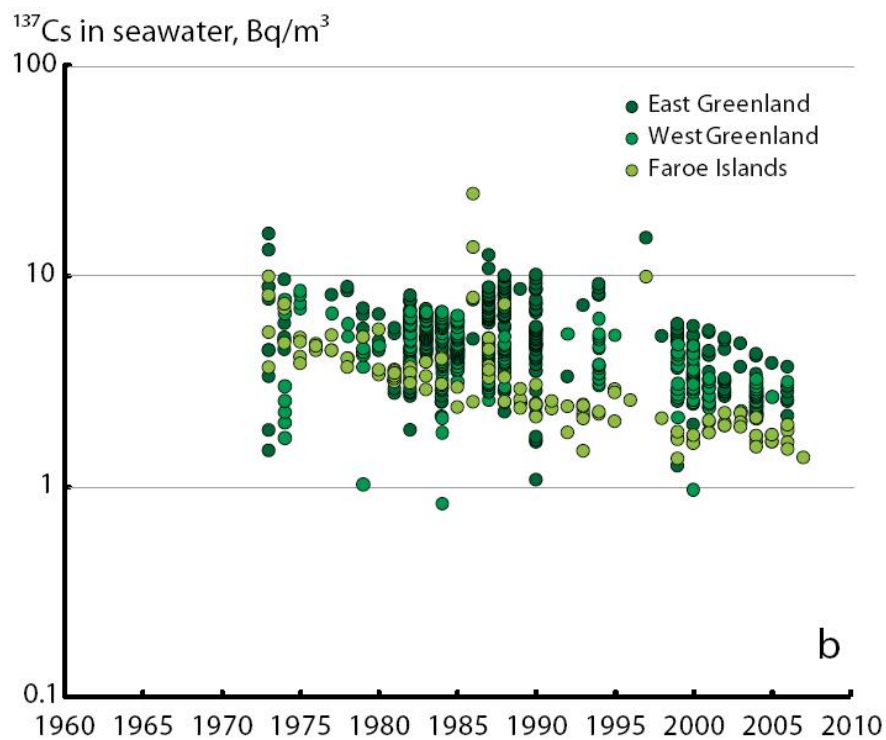


Fig. 9. Cs-137 in seawater off the coasts of the Faroe Islands and Greenland.

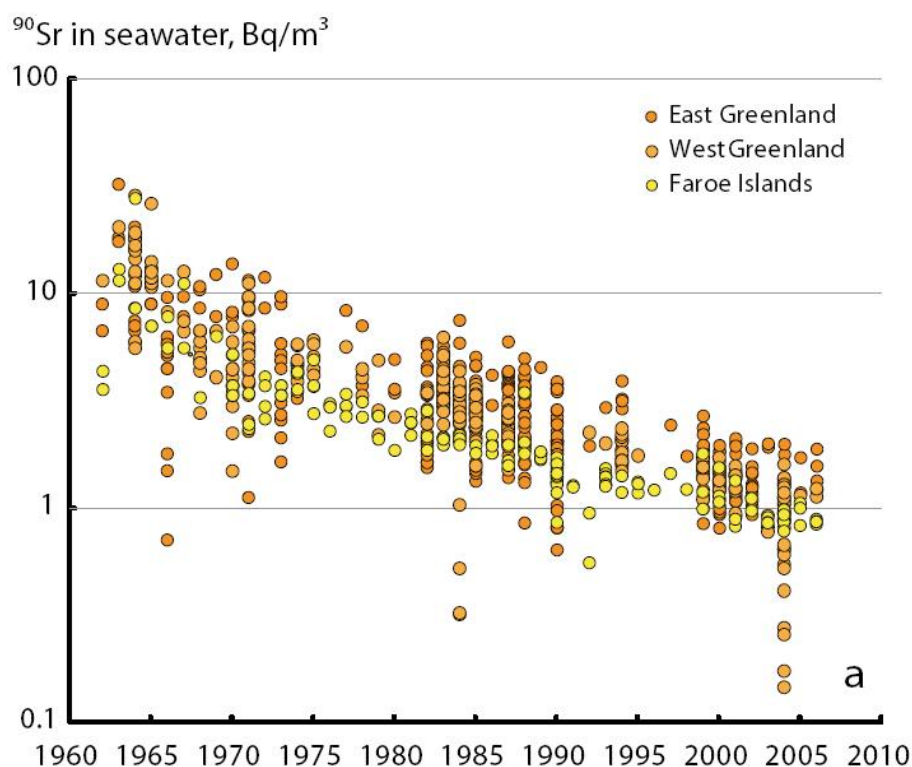


Fig. 10. Sr-90 in seawater off the coasts of the Faroe Islands and Greenland.

References

AMAP Assessment 2009: Radioactivity in the Arctic. Oslo 2010. ISBN 13 978-82-7971-059-2

Aure, J. et al., 1998. Havets miljø 1998. Fisken og havet, særn. 2. Bergen: Havforskningsinstituttet. (In Norwegian)

Dahlgaard, H.; Hansen, B.; Joensen, H.P. Observations of radioactive tracers in Faroese waters. ICES, C.M. 1991/C:26

Hansen, B. 2000. Havið (*The Ocean*) ISBN: 99918-0-248-7. (In Faroese)

3.3 Iceland

S. E. Pálsson

The following are excerpts from the MARICE-E-report MER-13-2012, which give a glimpse of the structure of the marine model used at the University of Iceland and which will be used for further work within COSEMA.

Introduction

In order to simulate the hydrography of Icelandic waters the workgroup MARICE at the University of Iceland has developed the numerical ocean model CODE. With this report a detailed description of the recent model version CODE 9.221 is given and its output is presented: the hydrography of Icelandic waters during the time period 1992 to 2006. The model was forced by the 6 hourly NCEP/NCAR re-analysis atmospheric fields. Daily river discharge data of 58 Icelandic rivers, estimated by the hydrological model WaSiM operated by the Icelandic Meteorological Office, were included as well as all available CTD profiles recorded from 1992 to 2006 in Icelandic waters. The CTD data was assimilated into the simulation. I.e. with an iterative procedure correction terms were determined which minimised the deviation between simulated and observed temperature and salinity profiles.

The presentation of the model output is confined to charts of monthly mean flow, temperature and salinity at the depth of 50 m and to overall model error estimations. For a more profound analysis of the data set the reader is referred to the following publications of the authors.

Model description

CODE (Cartesian coordinates Ocean model with three-Dimensional adaptive mesh adaption and primitive Equations) is a three-dimensional, primitive equations, z-level, coupled seaice/ ocean model. The basic idea behind CODE is the simulation of basin-scale ocean dynamics (length scale in the order of 10000 km) including the small-scale structures, with length scales less than 10 km, of selected areas of interest. Additionally the computational costs of the simulation should be minimised to enable the computation of multi-decadal runs within an acceptable length of time. Both points could be realised using the technique of adaptive mesh refinement. Though this involves more complicated numerical methods the disadvantages of conventional nesting (higher computational effort, missing coupling between several model runs, numerical errors at open boundaries) or finite element (higher computational effort) approaches could be avoided. The simulation presented here – entire North Atlantic/Arctic Ocean with highly resolved (1 km) Icelandic waters – was computed on an Intel Xeon 3.33 GHz CPU and needed 92 hours for the simulation of one year.

First CODE application in COSEMA

Based on topographic and hydrographic criteria nine compartment boxes, horizontally dividing the Icelandic waters, were defined (Fig. 17 and Table 1). These definitions were transferred into the ocean model and a series of model experiments were carried out. Within these experiments the mean current and diffusion fields averaged over the

period 1992 to 2006 were used. At the beginning of each model run a mathematical tracer concentration was set to 1 within one of the boxes. Then the advective and diffusive spreading of this concentration was simulated. After the simulation time of 24 hours the model was stopped, and the according flux rates between the boxes were computed (Fig. 18).

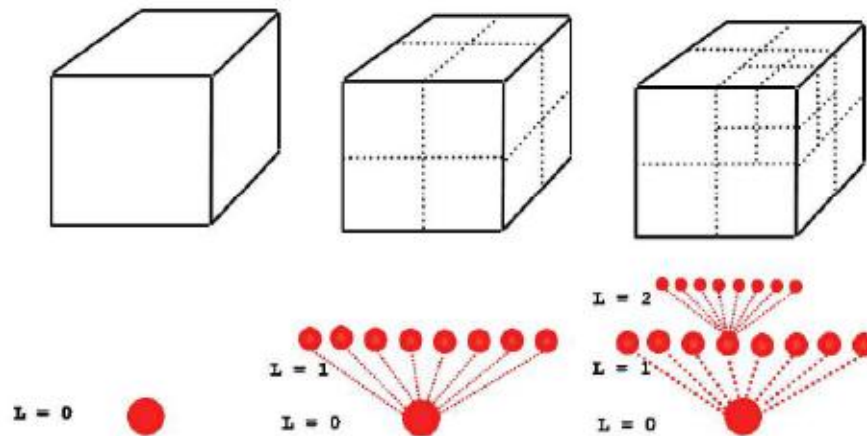


Fig. 11. Schematic process of adaptive grid refinement, following the algorithm of Khokhlov (1998). The large cube on the left side (adaption level 0) is split into 8 "children" of adaption level 1. Hence the model equations are no longer solved on the "parent cell". However, the "parent cell" is not removed from the computer's memory. It is obtaining the average properties of its children at each time step instead.

Overall view of model over the North Atlantic:

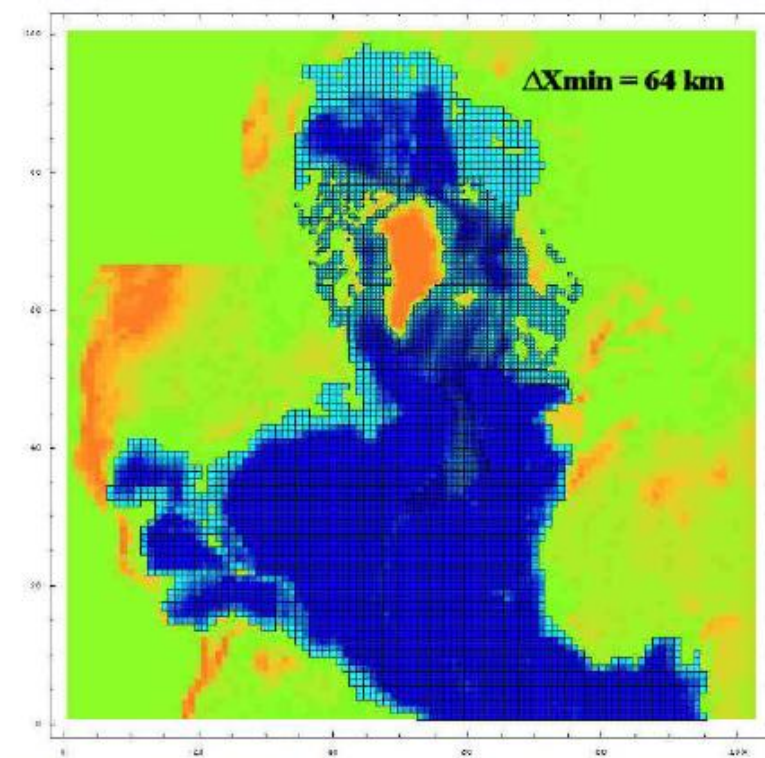


Fig. 12. The computational mesh after the first step of horizontal mesh refinement.

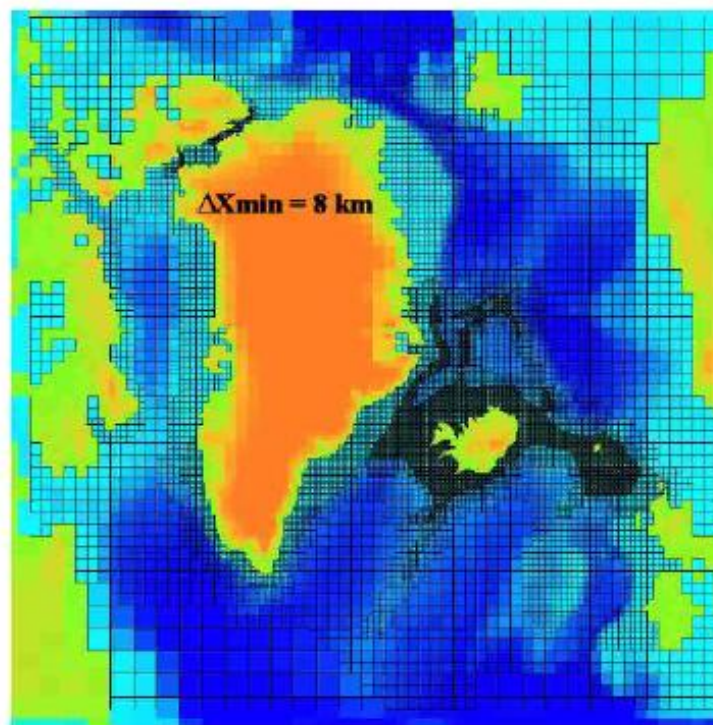


Fig. 13. The computational mesh after the fourth step of horizontal mesh refinement.

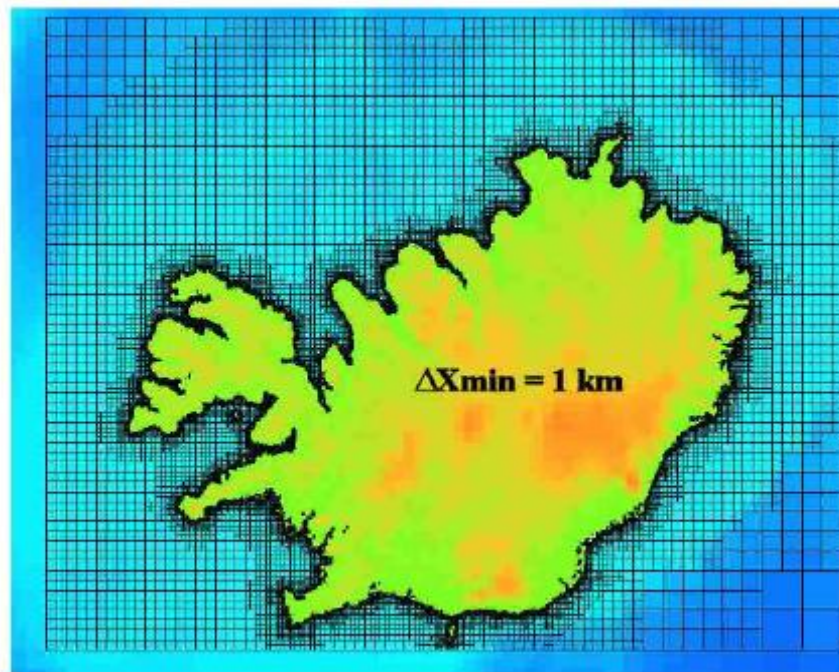


Fig. 14. The computational mesh after the final seventh step of horizontal mesh refinement.

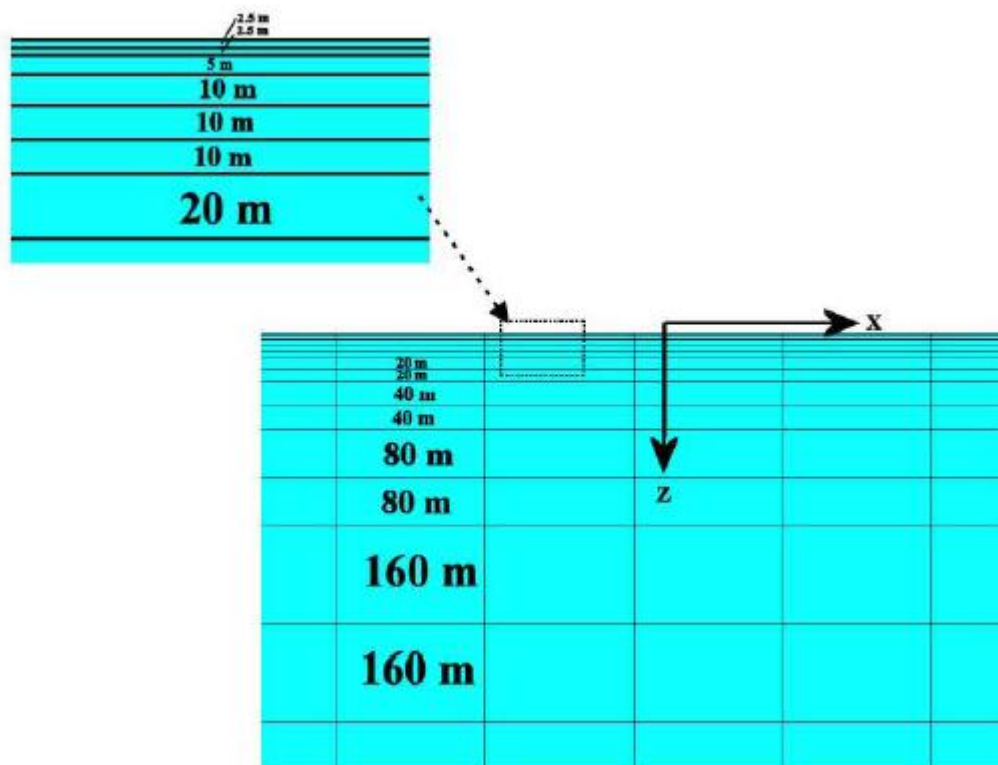


Fig. 15. The computational mesh's vertical structure.

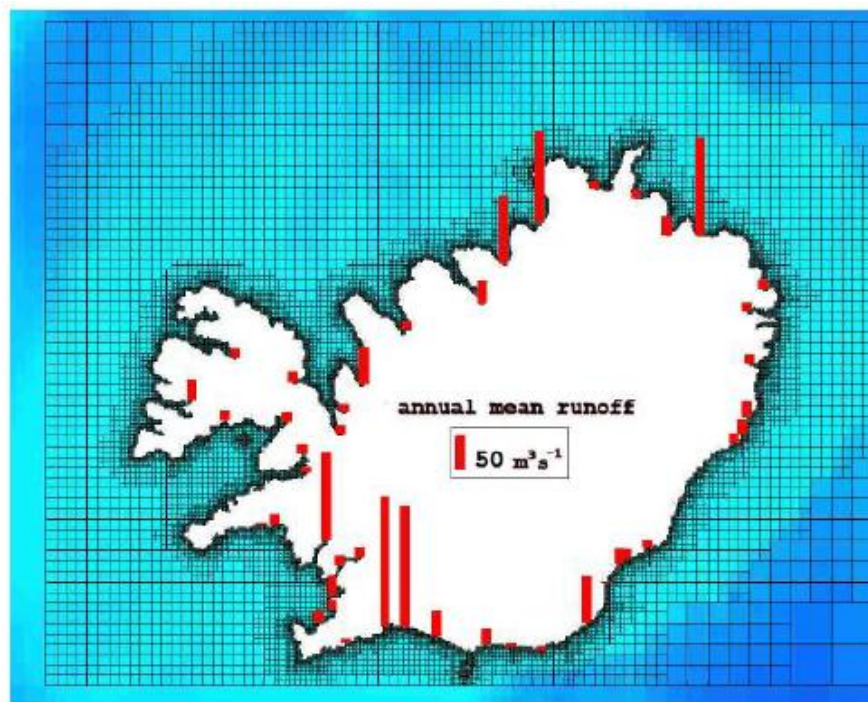


Fig. 16. The location and mean discharge of rivers included within the simulation.

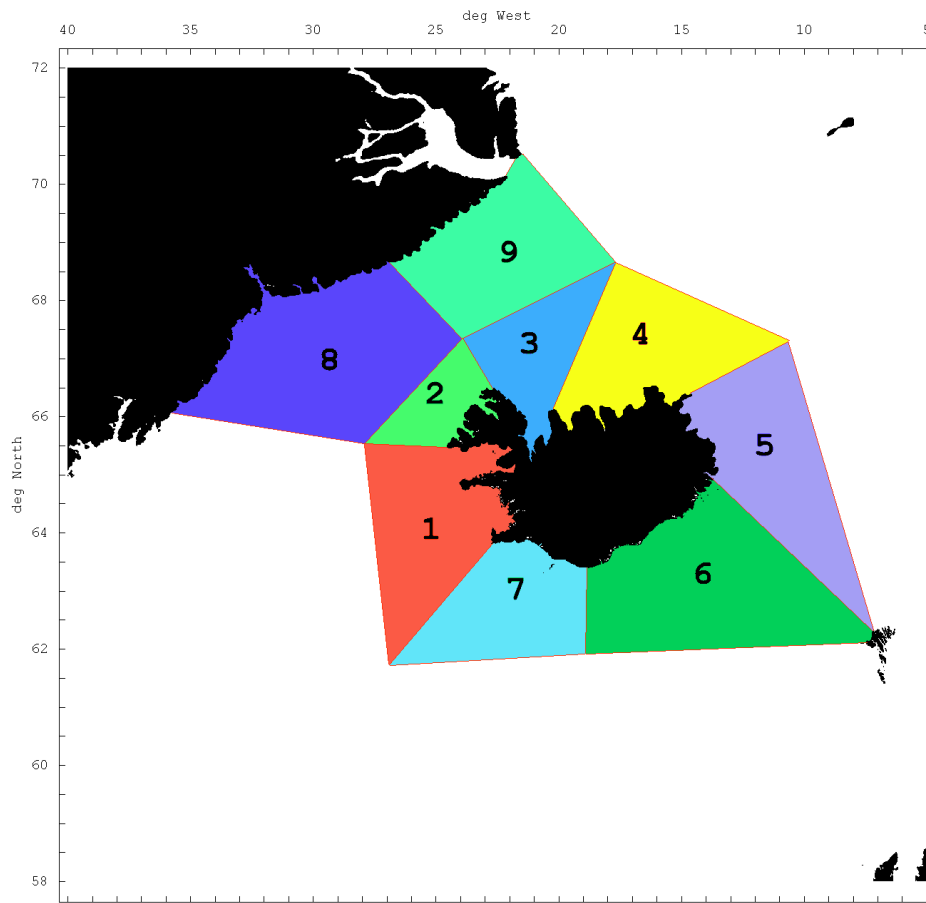


Fig. 17. Definition of compartmental boxes for COSEMA modelling.

Table 1. Volume and depth of boxes.

box no.	volume (m ³)	mean depth (m)
1	0.30875736E+14	0.41388681E+03
2	0.45874487E+13	0.19979407E+03
3	0.14862981E+14	0.39440656E+03
4	0.42704377E+14	0.69592224E+03
5	0.50321238E+14	0.62822296E+03
6	0.11065060E+15	0.92798999E+03
7	0.69452649E+14	0.10830667E+04
8	0.40931894E+14	0.41316107E+03
9	0.51804176E+14	0.84404614E+03

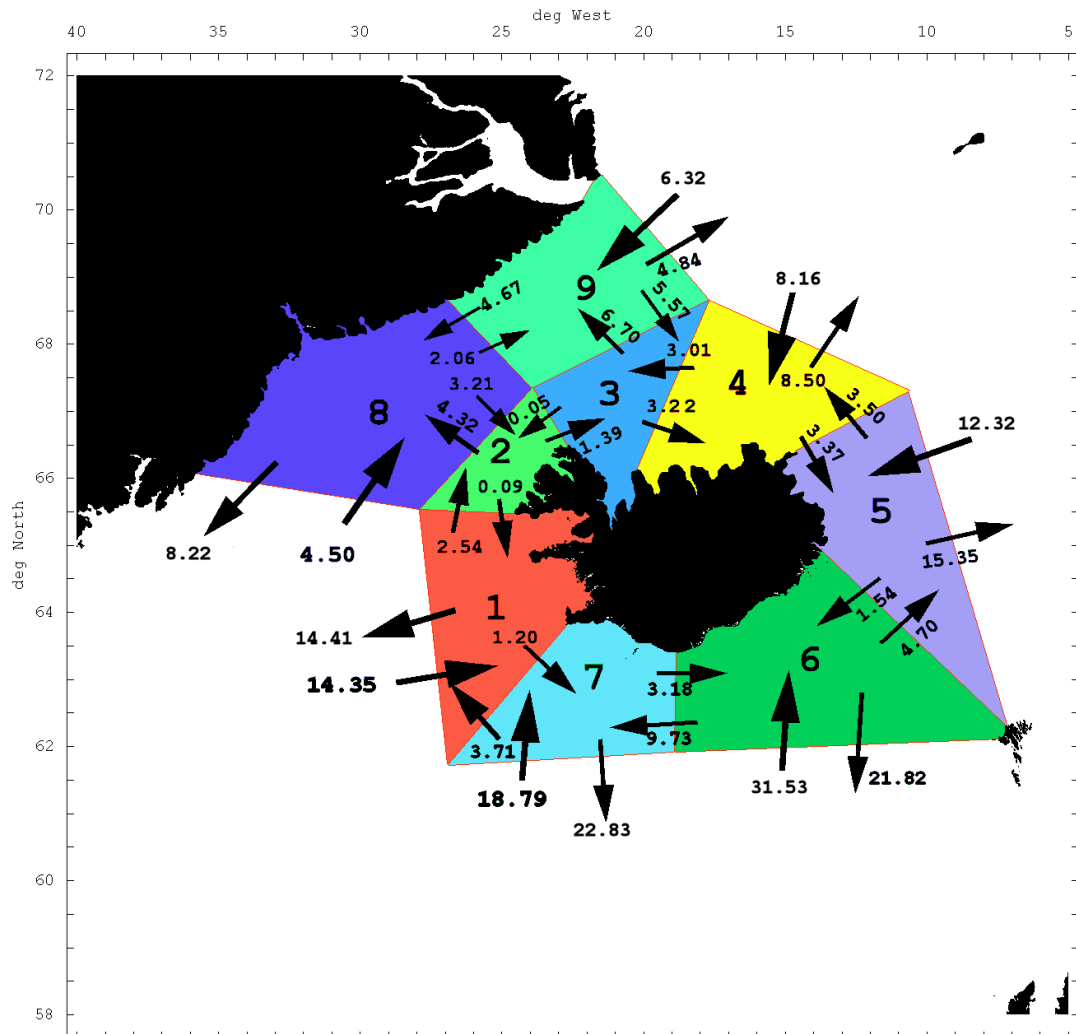


Fig. 18. Boxes with transfer parameters, flow rates between boxes in Sverdrup (1 Sv = $10^6 \text{ m}^3 \text{ m}^{-1}$).

References

Logemann, K. and Harms, I.: High resolution modelling of the North Icelandic Irminger Current (NIIC), *Ocean Sci.*, 2, 291-304, 2006.

Logemann, K., Olafsson, J., and Marteinsdóttir, G.: The ocean model CODE and its application to Icelandic waters, MARICE E-report MER-10-2010, University of Iceland, pp. 93, <http://www.marice.is/ereports/MER-10-2010.pdf>, 2010.

Logemann, K., Olafsson, J. & Marteinsdóttir, G. 2012. Modelling the hydrography of Icelandic waters from 1992 to 2006. MARICE-E-report MER-13-2012 (<http://www.marice.is/ereports.htm>)

4 Radioactive source term analyses

4.1 NPP accident source term

J. Lahtinen

4.1.1 Background

At the project meeting in March it was decided that the releases to the ocean in Fukushima should be used as a basis of the COSEMA source term. It is known that the situation in Fukushima was quite a complex one: there were three reactor facilities affected and there were planned and unplanned releases. In addition, deposition of airborne radioactive releases onto sea also constituted a source that – according to some estimates – is about the same order or even bigger as the direct releases to the ocean. Rain water washout of contaminated soils has also been mentioned but this contribution will become detectable in course of time as the concentrations along the coast have decreased.

Several papers and other documents addressing the marine source term of Fukushima have been published (see the list of references). Some assessments rely mostly on measurements of concentrations in sea water, some on measurements and model calculations, and a few primarily on calculations. Most documents deal only with caesium (^{137}Cs , ^{134}Cs) and (sometimes) ^{131}I . Estimated quantitative values of direct releases to the ocean vary, although it is generally agreed that the planned release of waste water which was “slightly contaminated” is insignificant as compared to the unplanned releases:

- ^{137}Cs : from 3.5 to 27 PBq.
- ^{134}Cs : about the same as for ^{137}Cs .
- ^{131}I : from 11 to about 80 PBq.

Better and more reliable estimates are likely to be available after the UNSCEAR report will be published (Weiss, 2012).

STUK, which was responsible for defining the NPP source term to be used in COSEMA calculations, decided to use the paper of Bailly du Bois et al. (2011) as the basic source for source term estimation. It is likely that the source term – described originally in the project document “Marine source term of Fukushima NPP accident for NKS/COSEMA project” (Lahtinen; STUK, rev. 2 9.5.2012) – is conservative; this was discussed briefly at the project meeting in Oslo in September but no changes were made.

One of the reasons to use the paper of Bailly du Bois as a corner stone was that it is based on measurements and that it considers also some other nuclides than caesium isotopes and ^{131}I .

4.1.2 Fukushima source term

Bailly du Bois et al. (2011) took the advantage of measurement results when estimating the marine source term of Fukushima (Fig. 19). They derive the following conclusions:

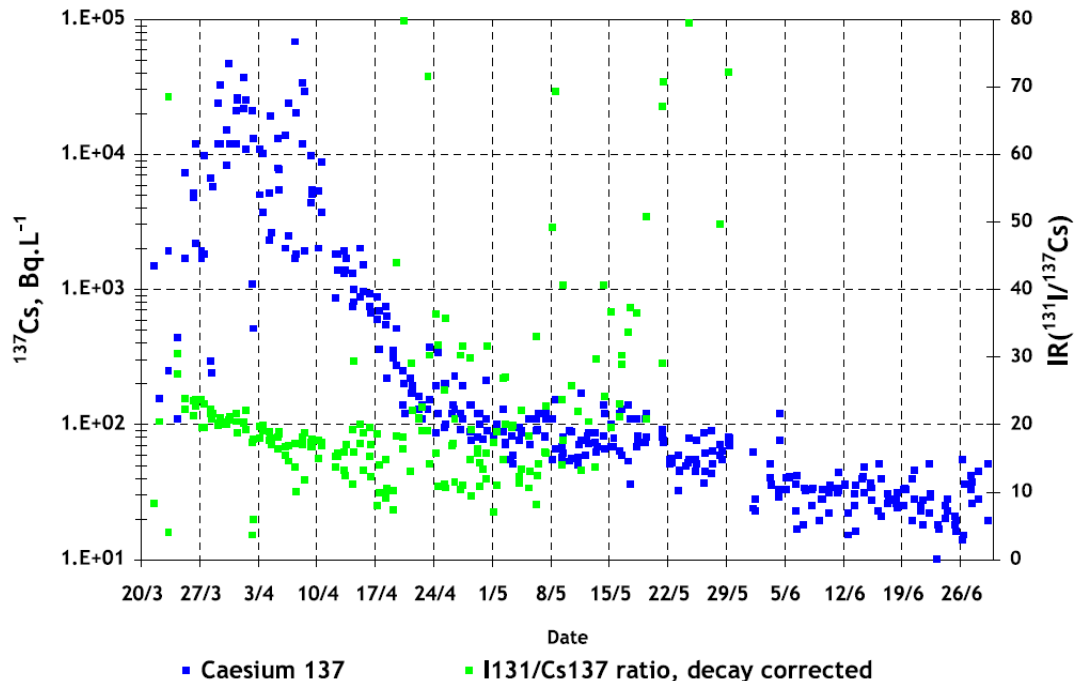


Fig. 19. Evolution of ^{137}Cs concentrations and $^{131}\text{I}/^{137}\text{Cs}$ ratios in sea water at less than 2 km from the Fukushima Dai-ichi power plant (Bailly du Bois et al., 2011).

- Release of 27 PBq (12 PBq – 41 PBq) of ^{137}Cs from March 21 to July 18.
- $^{134}\text{Cs}/^{137}\text{Cs}$ concentration ratio was close to 1 and the decay-corrected $^{131}\text{I}/^{137}\text{Cs}$ ratio close to the plant was 24–18 from March 26 to April 8.
- $^{90}\text{Sr}/^{137}\text{Cs}$ and $^{99}\text{Tc}/^{137}\text{Cs}$ concentration ratios were 0.02 and 0.01 respectively (rough estimates).

In order to define a source term based on Bailly du Bois et al. one can make the following assumptions:

- In Fukushima all contaminated water was released from the core of Unit 2 (BWR type, 760 MW_e, 2380 MW_{th}). (This of course is not true.)
- The release took place from March 26 to April 8.
- ^{134}Cs and ^{137}Cs activity concentrations in sea water were the same.
- Decay-corrected $^{131}\text{I}/^{137}\text{Cs}$ concentration ratio in water was 20.
- $^{90}\text{Sr}/^{137}\text{Cs}$ and $^{99}\text{Tc}/^{137}\text{Cs}$ concentration ratios in water were 0.02 and 0.01 respectively.
- Total ^{137}Cs release was 25 PBq.

From the above the released (decay-corrected for I-131) total activities can be estimated:

- ^{137}Cs : 25 PBq (corresponds approximately to a release fraction of 11 %)¹.
- ^{134}Cs : 25 PBq (11 %)¹
- ^{131}I : 500 PBq (23 %)¹
- ^{90}Sr : 0.5 PBq (0.3 %)¹
- ^{99}Tc : 0.25 PBq (^{99}Tc activity originates apart from direct fission also from the decay of ^{99}Mo and $^{99\text{m}}\text{Tc}$ -99)²

If one follows here the same conventional procedure as in the case of releases to the atmosphere, the caesium release fraction given above can be applied to the caesium group (see Table 2), ^{131}I release fraction to the iodine group and ^{90}Sr release fraction to the strontium group. ^{99}Tc implies that nuclides in the ruthenium group were also released. This is supported by the fact that ^{58}Co was detected in the water too (TEPCO, 2011). In addition, tellurium (and ^{132}I) was found (IRSN, 2011a; IRSN, 2011c).

Table 2. Nuclide groups (NUREG, 1990)³.

Inert gases	Kr-85, Kr-85m, Kr-87, Kr-88, Xe-133, Xe-135
Iodine	I-131, I-132, I-133, I-134, I-135
Cesium	Rb-86, Cs-134, Cs-136, Cs-137
Tellurium	Te-127, Te-127m, Te-129, Te-129m, Te-131m, Te-132, Sb-127, Sb-129
Strontium	Sr-89, Sr-90, Sr-91, Sr-92
Ruthenium	Co-58, Co-60, Mo-99, Tc-99m, Ru-103, Ru-105, Ru-106, Rh-105
Lanthanum	Y-90, Y-91, Y-92, Y-93, Zr-95, Zr-97, Nb-95, La-140, La-141, La-142, Pr-143, Nd-147, Am-241, Cm-242, Cm-144
Cerium	Ce-141, Ce-143, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241
Barium	Ba-139, Ba-140

¹ The nominal equilibrium inventory of the Olkiluoto BWR (2500 MW_{th}) is used as a reference. Note that the actual Fukushima inventory depends on the fuel burn-up and the power history before scram (and also partly on the fuel composition details).

² ^{99}Tc activities are normally not given in the lists of important radionuclides in a reactor.

³ There also exist groupings that differ a bit from the one presented here.

4.1.3 COSEMA source term

The nuclear power plant sites in COSEMA are Loviisa (PWR, 1500 MW_{th}), Forsmark (BWR, 3300 MW_{th}), Ringhals (PWR, 3135 MW_{th}) and Oskarshamn (BWR, 3300 MW_{th}). There are several units at every site but those mentioned have the greatest thermal power. If actual inventories are not available, the inventories of the Loviisa and Olkiluoto reactors can be scaled and used in calculations.

As a very crude approximation one may assume that the release fraction for the tellurium group is the same as that for caesium and the release fraction for the ruthenium group is the same as that for strontium. Taking this and the reasoning in the preceding section into account the release fractions for the COSEMA studies are chosen to be: iodine 20 %, caesium 10 %, tellurium 10%, strontium 0.5 %, ruthenium 0.5 %. Other groups with smaller release fractions can be considered if needed.

It is realistic to assume that there is a delay between the reactor shutdown and start of the release. A 10-hour delay could be used, for example.

Two release periods are to be considered: three days and three weeks.

References

Bailly du Bois P., Laguionie P., Boust D., Korsakissok I., Didier D., Fievert B. (2011). *Estimation of marine source-term following Fukushima Dai-ichi accident*. Journal of Environmental Radioactivity (2011), doi:10.1016/j.jenvrad.2011.11.015. Available online 14 December 2011.

Buesseler K., Aoyama M., Fukasawa, M. (2011). *Impacts of the Fukushima nuclear power plants on marine radioactivity*. Environmental Science & Technology 45; 23; 9931–9935.

EC (2012). *Rasff News. Food Information Exchange. News: 11-653-add30*. European Commission, Health & Consumers Directorate-General. January, 2012.
http://ec.europa.eu/energy/nuclear/radiation_protection/doc/emergencypreparedness/20120103_infomsg.pdf.

IRSN (2011a). *Impact on marine environment of radioactive releases from the Fukushima-Daiichi nuclear accident*. IRSN, 13th May 2011.
http://www.irsn.fr/EN/news/Documents/IRSN_Fukushima-Accident_Impact-on-marine-environment-EN_20110513.pdf

IRSN (2011b). *Synthèse actualisée des connaissances relatives à l'impact sur le milieu marin des rejets radioactifs du site nucléaire accidenté de Fukushima Dai-ichi*. IRSN, 26th October 2011.
http://www.irsn.fr/FR/Actualites_presse/Actualites/Documents/IRSN-NI-Impact_accident_Fukushima_sur_milieu_marin_26102011.pdf.

IRSN (2011c). *Fukushima Ocean Release Study, Now In English*. English translation of the above document IRSN (2011b). <http://www.simplyinfo.org/?p=3818>.

IRSN (2012). *Summary of the Fukushima accident's impact on the environment in Japan, one year after the accident*. IRSN, 29rd February 2012. [http://www.irsn.fr/EN/publications/thematic/fukushima/Documents/IRSN Fukushima-Environment-consequences_28022012.pdf](http://www.irsn.fr/EN/publications/thematic/fukushima/Documents/IRSN_Fukushima-Environment-consequences_28022012.pdf).

Katata G., Ota M., Terada H., Chino M., Nagai H. (2011). *Atmospheric discharge and dispersion of radionuclides during the Fukushima Dai-ichi Nuclear Power Plant Accident*. Journal of Environmental Radioactivity 109; 1; 103–113.

Kawamura H., Kobayashi T., Furuno A., In T., Ishikawa Y., Nakayama T., Shima S., Awaji T. (2011). *preliminary numerical experiments on oceanic dispersion of ¹³¹I and ¹³⁷Cs discharged into the ocean because of the Fukushima Daiichi nuclear power plant disaster*. Journal of Nuclear Science and Technology 48; 11; 1349–1356.

NERH (2011). *Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety. The Accident at TEPCO's Fukushima Nuclear Power Stations*. Nuclear Emergency Response Headquarters, Government of Japan. June 2011. http://www.kantei.go.jp/foreign/kan/topics/201106/iaea_houkokusho_e.html.

NUREG (1990). *Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants*. Final Summary Report. U.S. Nuclear Regulatory Commission, NUREG-1150.

TEPCO (2011). <http://www.tepco.co.jp/en/nu/fukushima-np/f1/index2-e.html>.

Tsumune T., Tsubono T., Ayonoma M., Hirose K. (2011). *Distribution of oceanic ¹³⁷Cs from the Fukushima Dai-ichi Nuclear Power Plant simulated numerically by a regional ocean model*. Journal of Environmental Radioactivity (2011), doi:10.1016/j.jenvrad.2011.10.007. Available online 8 November 2011.

Weiss, W. (2012). *Preparing a scientific report to the General Assembly on 'Exposures due to the nuclear accident following the Great East-Japan earthquake and tsunami'*. Journal of Radiological Protection 32; 1; N113–N118. doi:10.1088/0952-4746/32/1/N113. Available online 6 March 2012.

In addition, a special issue of the Journal of Environmental Radioactivity (volume 111, September 2012) *Environmental Impacts of the Fukushima Accident (Part I)* contains some papers dealing with releases to the sea.

4.2 Submarine accident source term

M. Iosjpe

Inventory

The source term consists of an inventory of radionuclides, released as a function of time and a release point. Each of these elements will be described below.

The core inventory has primarily two components: the fuel matrix itself and the fuel burn-up. While the fuel matrix itself has only indirect influence on the amount of fission products, the amount of transuranics and release rates will depend directly on the type of matrix. In the current work, with its emphasis on a credible approach, the most probable representation of a Russian third-generation submarine core is a core load with 63% enriched fuel with 259.7 kg U-235 in a dispersion ($\text{UO}_2\text{-Al}$ / $\text{UO}_2\text{-Zr}$) or intermetallic configuration ($\text{UAl}_x\text{-Al}$) (Reistad, 2008). This composition has been verified to fit the only suggested core geometry for other than first-generation Russian submarines. However, as there exist an indefinite number of core configurations corresponding to various fuel volumes, the selection criterion has been to apply similar fuel density (4.5 Ug/cm^3) as that reported for Russian floating nuclear power plants under construction (Chuen and Reistad, 2007). A maximum credible inventory has been developed on the basis of a conservative approach to the average annual burn-up for third-generation reactors.

Average annual burn-up has been calculated to 30 effective full-power days (EFPD) and the maximum operational period hypothetically set to 20 years. At present, the average life-span for this class of vessels is 13.2 years. As the current decommissioning rate is higher than the commissioning rate, we may assume that this value will decrease slowly in the future. However, as the selection criterion has been a maximum credible burn-up, and normal vessel life is more than 13.2 years, we may assume 20 years of operation as a conservative estimate as a basis for calculating the radionuclide inventory at the time of the accident. The resultant burn-up is 114,000 MWd, or 269,000 MWd/tons of heavy metal. We have also assumed an operating power fraction of 0.5 at the time of accident, resulting in a high inventory of short-lived isotopes when the hypothetical accident occurs. The core inventory and core decay heat were developed using HELIOS 1.8 and SNF 1.2. HELIOS is a detailed reactor physics transport and burn-up code developed and supported by Studsvik Scandpower (Reistad, 2008).

Accident scenario

The hypothetical scenario forming the basis for this study, is if a core-melt / loss-of coolant accident (LOCA) (Reistad, 2008) was to occur together with another type of incident, such as an explosion. Then there would be a credible risk of substantial damage to all parts of the submarine. An explosion that ruptured the hull and provided water intrusion in the reactor compartment would also contribute to cooling the corium.

In this study, we will use the scenario described in Table 3, which corresponds to Scenario 1 from (Reistad, 2008).

Table 3. Release fractions for maximum credible accident for third-generation submarine.

	Phase 1: From t=0.1 days to t=1 year	Phase 2: From t=1 year
Coremelt release	Immediate release of release fraction as given in Table 4 (High flux reactor)	
Fuel corrosion	Constant release of fuel corrosion products: corrosion rate: 0.01 % of fuel material annually	

Release fractions

The main methodological problem here is the lack of relevant information on fuel materials, and secondly, on radionuclide behavior in fuel matrixes under extreme conditions (high temperature, saltwater intrusion etc.). However, a civilian nuclear system with potentially similar attributes to those of third-generation reactors – high power densities, high enrichment levels and moderate burn-up levels (50%) – is found in civilian research reactors. The hypothetical correspondence in fuel design and fuel properties has formed the basis for assessments of fuel consumption, as in (Reistad,2008). Few civilian research facilities have been analyzed on the basis of probabilistic methods; deterministic accident analysis remains the most applied method for these facilities. The source term evaluation for research facilities displays differences similar to those shown in Table 4, describing the release fractions for three HEU (highly enriched uranium) highly enriched uranium highly enriched uranium - fueled research reactors.

Table 4. Release fractions in the case of core meltdown following a LOCA (Abou Yehia and Bars, 2005).

	HIFAR	High flux reactor	SAFARI
Noble gases	1	1	1
I	0.3	0.8	1
Br		0.8	
Cs	0.3	0.8	0.163
Te	0.01	0.8	0.192
Rb	0.3	0.01	
Ru	0.01	0.1	0.005
Ba, Rh, Sr		0.1	
Actinides		0.01	0.1
Other		0.01	

The second component of the release fraction is fuel degradation and corrosion. Based on the hypothesis of the fuel matrix and the accident scenario, the corrosion processes of the uranium-loaded fuel component, UO_2 or UAl_x , starts immediately when the seawater enters the primary circuit. Experiments for long-term dissolution of fuel elements in seawater obtained dissolution rates from 0.1 to 1% of the fuel per year at temperatures from 10 to 20°C (Petrov, 1991).

Release Scenario

The total and the individual releases of the radionuclides that had the most significant effect on the release rates during the initial and later phases of accidental releases are presented in Figure 20. As expected, the maximum release occurs during the initial period after the accident (the instant release fraction) with maximum values of $1.6 \cdot 10^{18}$ Bq at the beginning of release. Figure 20 shows that short-lived radionuclides of iodine and barium are most significant during the initial phase of release according to the present scenario, while ^{90}Sr and ^{137}Cs dominates in the final period of release.

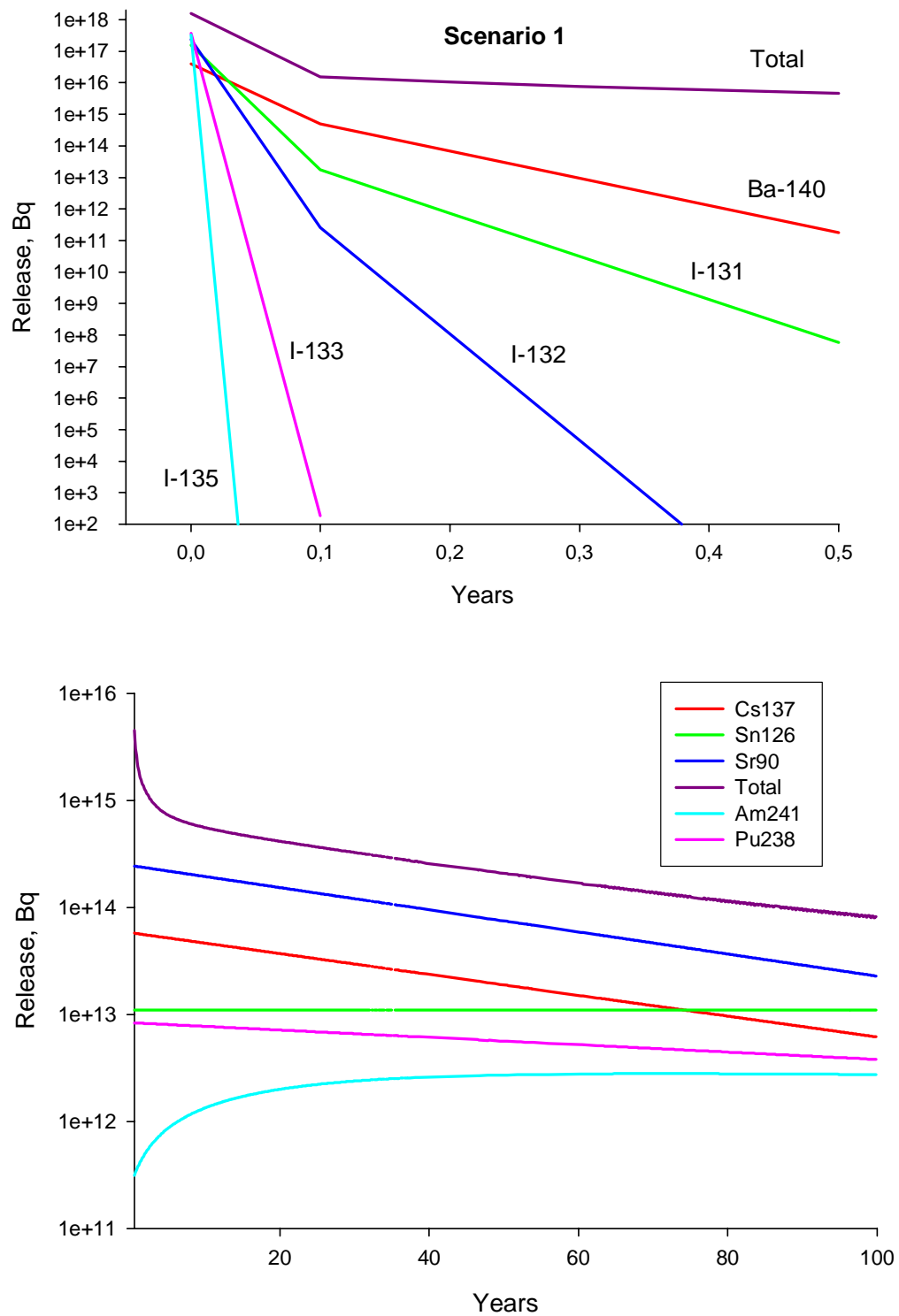


Fig. 20. The release scenario for the initial time of 0-0.5 year (top) and for the time 0.5-100 years (bottom)

References

Abou Yehia H. and G. Bars, 2005. Disparities in the safety demonstrations for research reactors and the need for harmonization. In: Joint Meeting of the National Organization of Test, Research, and Training Reactors and the International Group on Research Reactors, September 12-16, Gaithersburg, MD, 2005.

<http://www.ncnr.nist.gov/trtr2005/Proceedings/Abou-Yehia%20-%20Disparities%20in%20safety%20Demonstrations.pdf>

Chuen C. and O. Reistad (2007). Sea Fission – Russia's Floating Nuclear Power Plants. *Jane's Intelligence Review* 2007, 19(12), 48 – 52.

Iosjpe M., Reistad O., Liland A. (2011). Radioecological consequences after a hypothetical accident with release into the marine environment involving a Russian nuclear submarine in the Barents Sea StrålevernRapport 2011:3. Østerås: Statens strålevern, 2011.

Petrov, E., 1991. Estimation of the Nuclear Power Plant Condition and Radiation and Ecological Consequences of a Prolonged Stay of the SSN 'Komsomolets' on the Sea Bed and During Its Recovery, (unpublished), submitted from the Russian Central Design Bureau Marine Engineering "Rubin" to the Norwegian Government, November 15, 1991.

Reistad, O., S. Hustveit & S. Roudak, 2008. Operational and Accident Survey of Russian Nuclear Submarines for Risk Assessments using Statistical Models for Reliability Growth, *Annals of Nuclear Energy*, 35(11), 2126-2135.

Reistad O., 2008. Analyzing Russian naval nuclear safety and security by measuring and modeling reactor and fuel inventory and accidental releases. Doctoral thesis at NTNU, 2008:14.

5 Calculation scenarios

NPP accident at coast of the Gulf of Finland

V. Suolainen

As an example of consequences of severe nuclear accidents in the Baltic Sea area, a hypothetical severe nuclear power plant accident taken place at the northern coast of the Gulf of Finland, was preliminary modelled in the study. A current nuclear power plant with two reactor units and the local sea area is shown in Fig. 21. below.



Fig. 21. Nuclear power plant and local sea area.

The radioactive source term to sea water was determined from the core inventory of the VVER-1000 reactor (Anttila, 2005) and applying further the element specific release fractions obtained in the source term analyses of this study (chapter 4.1, J. lahtinen). The used fuel burn-up was 50 MWd/kgU. Total released amounts of activity of the considered severe reactor accident is presented in Table 5.

Table 5. Total amounts of activity released to sea in a hypothetical severe VVER-1000 accident. There is 71 tU in the core of the reactor.

Nuclide	Specific activity at shutdown (GBq/tU)	Core activity at shutdown (Bq)	Release fraction	Total release to sea (Bq), $t > 10$ h
C-14	$5.00 \cdot 10^1$	$3.55 \cdot 10^{12}$	0.2	$7.10 \cdot 10^{11}$
Co-60	$2.45 \cdot 10^4$	$1.74 \cdot 10^{15}$	0.005	$8.70 \cdot 10^{12}$
Sr-90	$3.96 \cdot 10^6$	$2.81 \cdot 10^{17}$	0.005	$1.41 \cdot 10^{15}$
Tc-99	$7.12 \cdot 10^2$	$5.06 \cdot 10^{13}$	0.005	$2.53 \cdot 10^{11}$
I-131	$3.56 \cdot 10^7$	$2.52 \cdot 10^{18}$	0.2	$4.85 \cdot 10^{17}$
Cs-134	$1.03 \cdot 10^7$	$7.29 \cdot 10^{17}$	0.1	$7.29 \cdot 10^{16}$
Cs-137	$5.87 \cdot 10^6$	$4.17 \cdot 10^{17}$	0.1	$4.17 \cdot 10^{16}$

In order to study the effect of duration of the release to consequences, a short-term release of 3 days (Figures 22 and 23) and a long-term release of 21 days (Fig. 24) were considered. The highest activity release rate is for iodine (I-131) which can clearly be seen from the linear scale Fig. 22.. Other important soluble release nuclides are C-134 and C-137.

In the long-term release assumption, the released total activity is dispersed for a longer time period. The effect of radioactive decay to the release rate of the short-lived I-131 can be seen from Fig. 24.

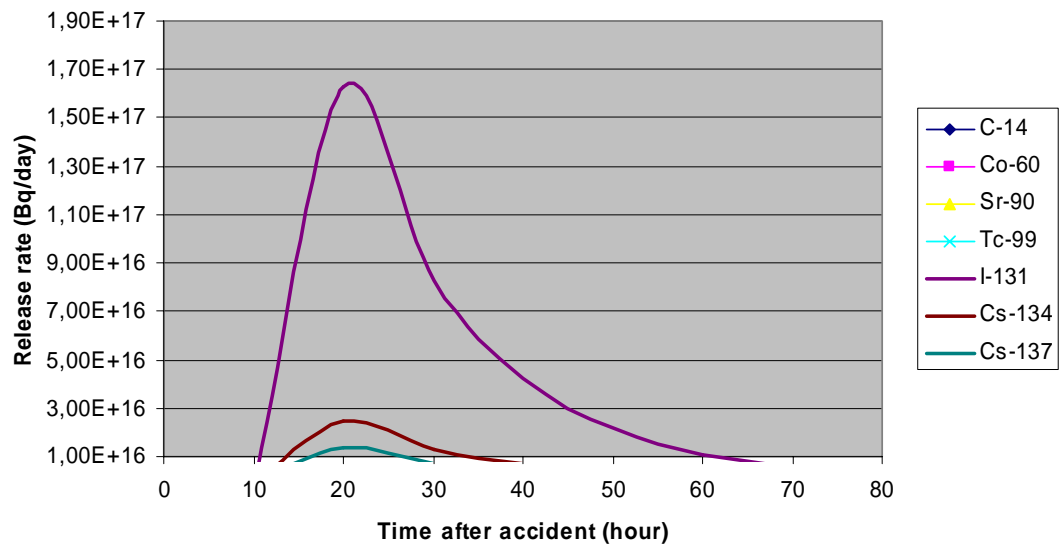
Short-term release (3 days)

Fig. 22. Release rates temporal behaviour presented in linear scale for the most important radionuclides I-131, Cs-134 and Cs-137.

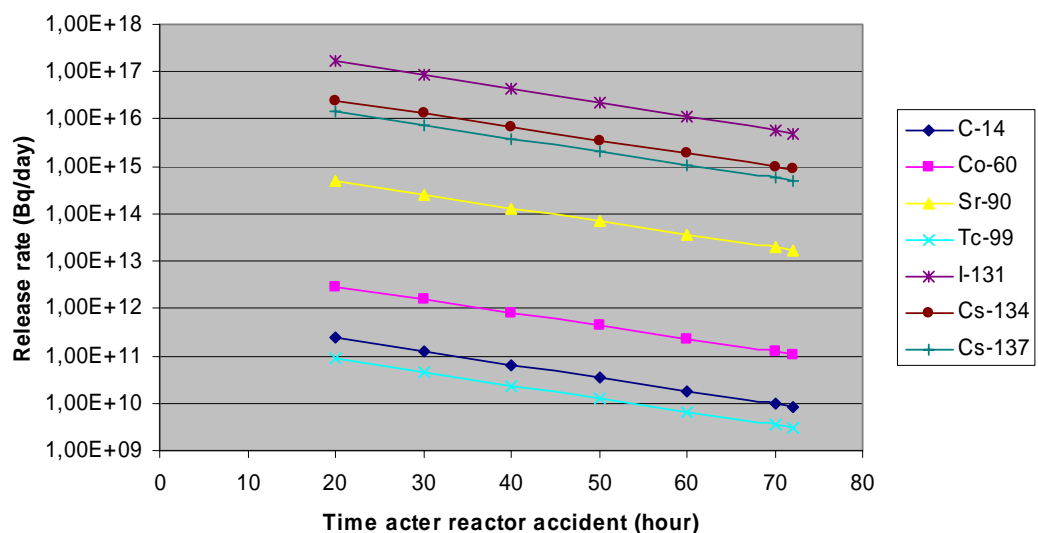
Short-term release (3 days) to sea

Fig. 23. Release rates of all important radionuclides in the short-term release assumption.

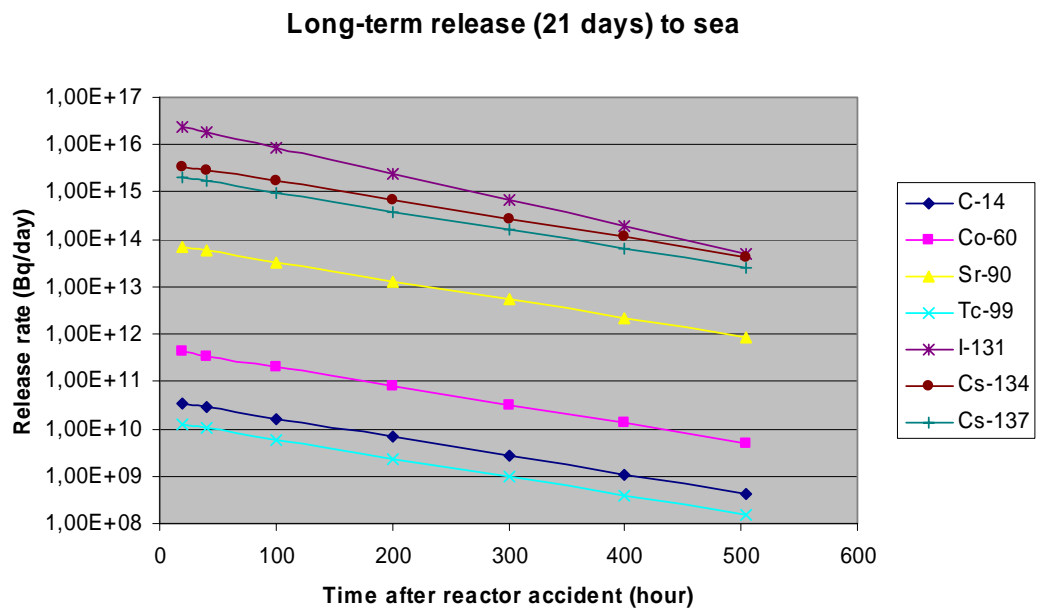


Fig 24. Release rates of important radionuclides in the long-term release assumption.

The aquatic transfer model consists of compartments for the local sea area close to nuclear power plant, the Gulf of Finland and the Baltic Sea dispersion area. Each water compartments has connection to bottom sediment layers (sedimentation term) and vice versa (resuspension term). Some main parameter values used in model calculations with Detra-code are presented in Table 6.

Table 6. Parameter values related to radionuclides transfer model of a hypothetical severe reactor accident at Gulf of Finland.

Water comp. characteristics		Local sea area	Gulf of Finland	Baltic Sea
volume (m ³)		1.0·10 ⁸	5.5·10 ¹¹	1.4·10 ¹³
water exchange rate (m ³ /a)		8.8·10 ⁸	6.0·10 ¹¹	5.0·10 ¹²
suspended sediment load (kg _s /m ³)		5.0·10 ⁻³	3.0·10 ⁻³	4.0·10 ⁻³
sedimentation rate (kg _s /m ² /a)		1.7·10 ⁻¹	1.7·10 ⁻¹	4.0·10 ⁻¹
Sediment characteristics		surface sediment		buried sediment
volume fraction of water		90%		72 %
resuspension of sedimented material		10 % of total sedimentation		
water exchange rate		1 a ⁻¹		
K _d -values (liter/kg _s)		C _{fish} (Bq/kg _r)/(Bq/liter) ; (IAEA TRS 422 & 472)		
C	100	2000		
Co	5000	1000		
Sr	10	2		
Tc	5000	30		
I	100	10		
Cs	1000	250		

The activity concentrations obtained in the local sea area water after a severe accident are very high, which is illustrated in Fig. 25. The large dilution capacity of the Gulf of Finland and the Baltic Sea will effectively decrease the radionuclide concentrations in sea water.

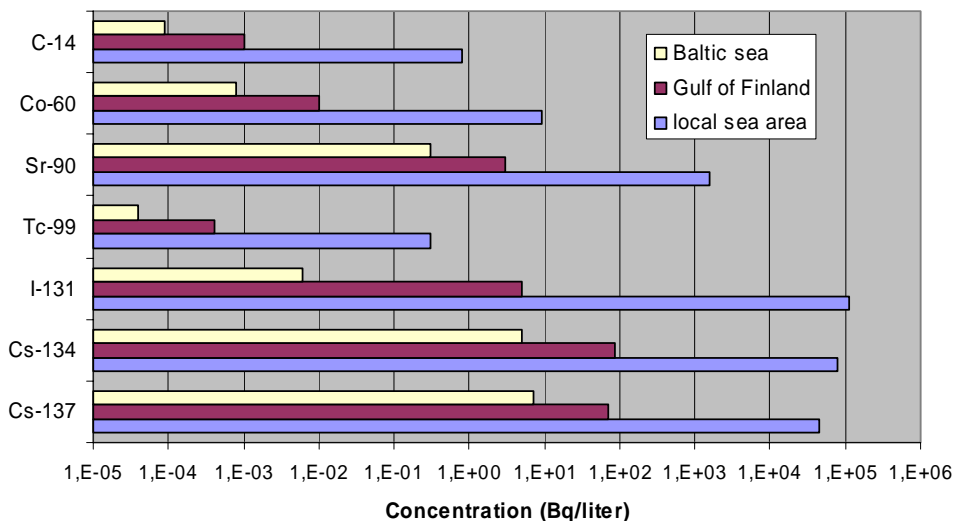
Radionuclide concentrations in sea water

Fig. 25. Maximum activity concentrations in sea water in local and areal scale after a severe reactor accident.

In case the highly contaminated sea food will be used by human, the arising doses would be high especially in local sea area (Fig. 26), total maximum annual individual dose about 600 mSv. Based on preliminary results the most important nuclides are Cs-134, Cs-137 and I-131 causing 96 % of the total ingestion dose.

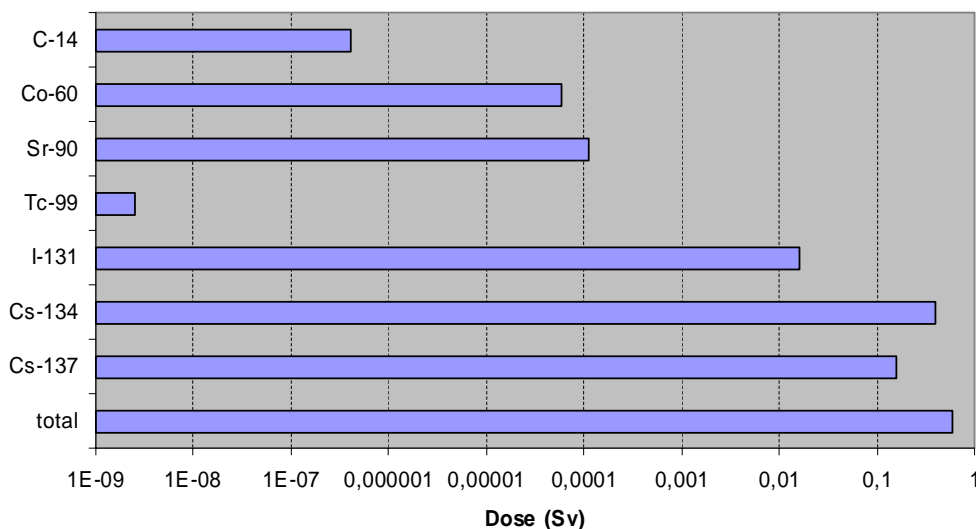
Individual doses via fish, local sea area

Fig. 26. Dose estimates for fish consumption from local sea area at the Gulf of Finland after a hypothetical severe reactor accident.

In the consideration of the Baltic Sea area, radionuclides concentrations of dominant long-lived nuclides (Cs-134, Cs-137) are about 1/10000 compared to concentrations obtained in the local sea area, close to the damaged NPP. Thus the arising maximum annual individual dose for fish dose pathway in the Baltic Sea area is in the level of 0.1 mSv.

References

Anttila, M., Radioactive characteristics of the spent fuel of the Finnish nuclear power plants, Posiva WR 2005-71.

IAEA TRS-422, Sediment distribution coefficients and concentration factors for biota in the marine environment, IAEA, Vienna, 2004, 93 p.

IAEA TRS-472, Handbook of parameter values for the prediction of radionuclide transfer in terrestrial and freshwater environments, IAEA, Vienna, 194 p.

Submarine accident at Iceland waters

M. Iosjpe

Brief description of the COSEMA compartment model

The COSEMA model is based on the methodology developed for the NRPA box model, which uses a modified approach for compartmental modeling (Iosjpe et al., 2002). This methodology allows for simulation of radionuclide dispersion over time.

The compartments, which include the volumes, mean depth and water exchanges between boxes for the Iceland coastal waters, were developed during the COSEMA project by Geislavarnir Ríkisins (Iceland). Additionally, two compartments surrounding the Iceland boxes were developed on the basis of the NRPA box model. The surface box structures for both models are shown in Figure 27.

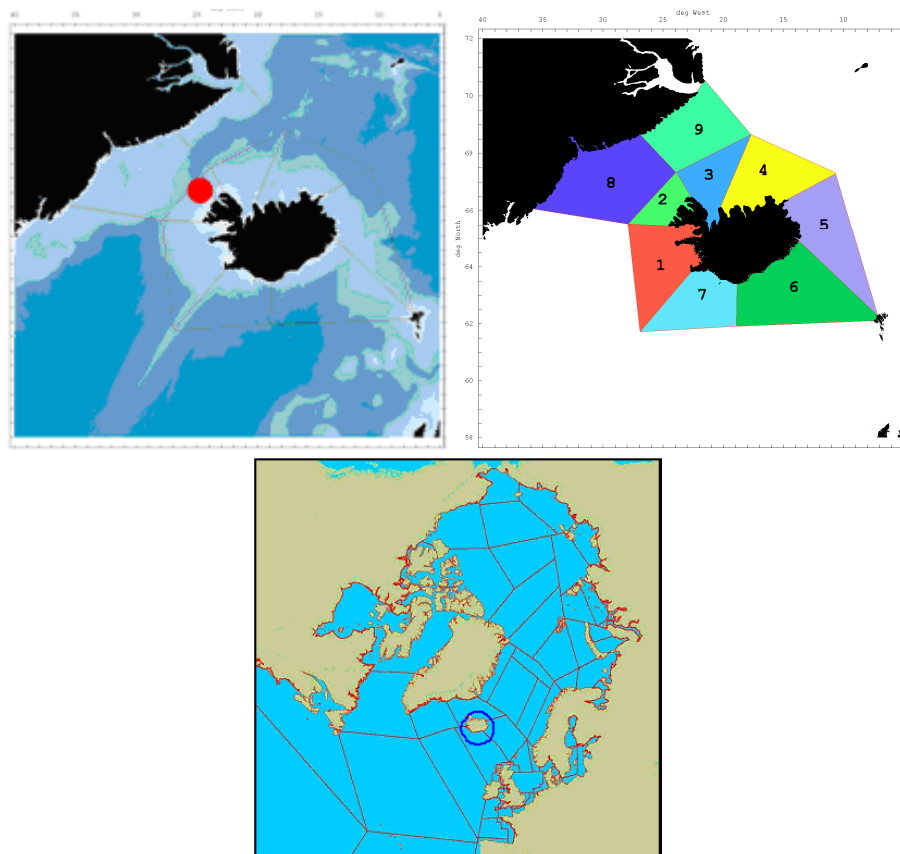


Fig. 27. The structure of the surface compartments in the COSEMA (top) and the NRPA (bottom) models and location of the potential accident (red dot).

The COSEMA model adopts the sediment structure from the NRPA model, including the surface, mid-depth and deep sediment compartments for all water regions. Water-sediment interactions include sedimentation, diffusion of radioactivity through pore

water in sediments, resuspension, mixing due to bioturbation, particle mixing and a burial process for radionuclides in deep sediment layers. Radioactive decay is calculated for all compartments. The contamination of biota is further calculated from the known radionuclide concentrations in filtered seawater in the different water regions. Collective doses to the world population are calculated on the basis of seafood consumptions, in accordance with available data for seafood catches and assumptions about human diet in the respective areas (Nielsen et al., 1997; EC, 2000; IASAP, 2003).

The collective dose D (manSv) can be determined using the following expression:

$$D = \sum_{j=1}^m DCF_j \sum_{l=1}^k \varphi_l \cdot CF_{lj} \sum_{i=1}^n A_{il} \int_0^T C_{ij}(t) dt, \quad (1)$$

where $[0, T]$ is the time interval (y); DCF_j (Sv/Bq) is the dose conversion factor for radionuclide j ($j = 1, 2, \dots, m$); CF_{lj} (m^3/t) is the concentration factor for radionuclide j in seafood of type l ($l = 1, 2, \dots, k$); A_{il} (t/y) is catch of seafood of type l in the model compartment i ; ($i = 1, 2, \dots, n$); C_{ij} (Bq/ m^3) is the concentration of radionuclide j in filtered seawater in model compartment i ; and φ_l is the edible fraction for seafood of type l . The following assumptions (CEC, 1990; EC, 2000; IASAP, 2003) for the edible fractions of marine produce to the human diet have been used: 50 % for fish, 35 % for crustaceans and 15 % for molluscs).

Collective dose rates DR can be defined using the following expression:

$$DR = \frac{D(t_2) - D(t_1)}{t_2 - t_1}, \quad (2)$$

where $D(t_1)$ and $D(t_2)$ are collective doses at times t_1 and t_2 , respectively.

It is necessary to note that the model can also easily be used to provide information on impact doses/dose rates from different marine regions, and provide dose assessment to different population groups. Furthermore, the dose rate will be used in the present dose assessment because this parameter can easily indicate dose dynamic and is therefore widely used in recent investigations (EC, 2003; IASAP; 2003).

Accident location

The location (the compartment 2 in Figure 28) chosen for the accident was based on an evaluation of the radiological sensitivity of different marine areas. Radiological sensitivity analysis of Arctic marine regions shows that the shallow waters can be considered as the most vulnerable areas in the Arctic region, in terms of the effects of possible radioactive contamination (Iosjpe et al., 2003; Iosjpe, 2011; Iosjpe & Liland, 2012).

Results and discussion

The radioecological consequences of the potential scenarios leading to accidental releases of radioactivity have been evaluated on the basis of the calculated concentrations of radionuclides in typical sea foods, collective dose rates to man and individual doses for the critical groups and doses to marine organisms.

Concentration of radionuclides in seafood

The Food and Agriculture organisation of the United Nations and World Health Organisation have provided recommendations (guideline levels) for the maximum permissible concentration of radionuclides in foods, when contaminated after an accidental release of radionuclides (CAC, 2006). According to the Codex Alimentarius Commission (CAC, 2006) radionuclides can be separated into four groups. Examples of some typical radionuclides for each group are presented in Table 7.

Table 7. Examples of international guideline levels for radionuclides in food.

Radionuclides in Foods		Guideline Level (Bq/kg)	
		Infant Foods	Other Foods
Group 1	^{238}Pu , ^{239}Pu , ^{241}Am	1	10
Group 2	^{90}Sr , ^{106}Ru , ^{129}I	100	100
Group 3	^{60}Co , ^{134}Cs , ^{137}Cs	1000	1000
Group 4	^3H , ^{14}C , ^{99}Tc	1000	10000

Following the CAC (2006) recommendations, the model calculations for fish, crustaceans and molluscs are provided separately for each group of radionuclides presented in Table 7.

It is clear that the highest level of sea food contamination is expected in box 2 (the accident location compartment). Results of the simulations of the radionuclide concentrations in seafood (fish, crustaceans and molluscs) for group 1 are shown in Figure 28. Results show the three most significant radionuclides in the group and the total concentration for the group.

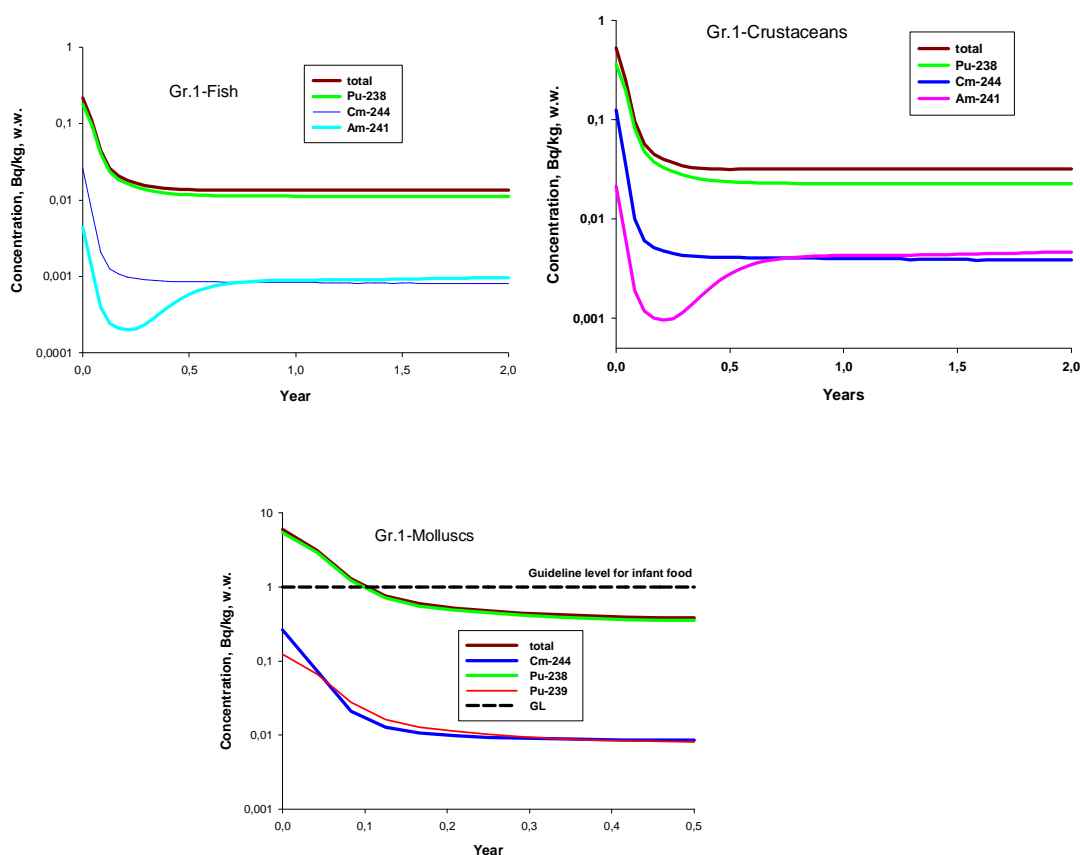


Fig. 28. Predicted concentration of radionuclides (Group 1) in sea food.

Results of the model calculations indicate that the concentration of radionuclides from group 1 in seafood lies significantly under the CAC guideline levels for fish and crustaceans, but considerably exceeding the CAC guideline level for molluscs for infant food during the first four weeks after the accidental release began. The total concentration level of radionuclides in seafood for group 1 is heavily dominated by ^{238}Pu . Therefore, it is interesting to note that the concentration of ^{238}Pu in compartment 2 is one to three orders of magnitude higher than in other boxes (results are presented in Figure 29).

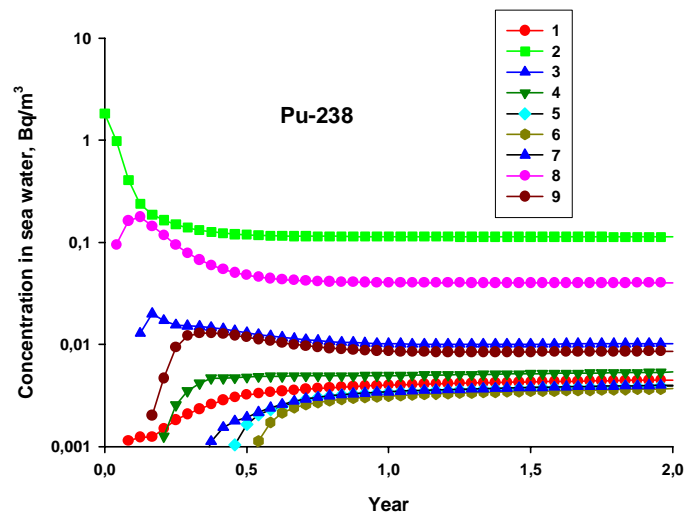


Fig. 29. Concentrations in sea waters in compartment 1-9.

Predicted concentration of Group 2 radionuclides in seafood is shown in Figure 30. The CAC guideline level is shown for comparison.

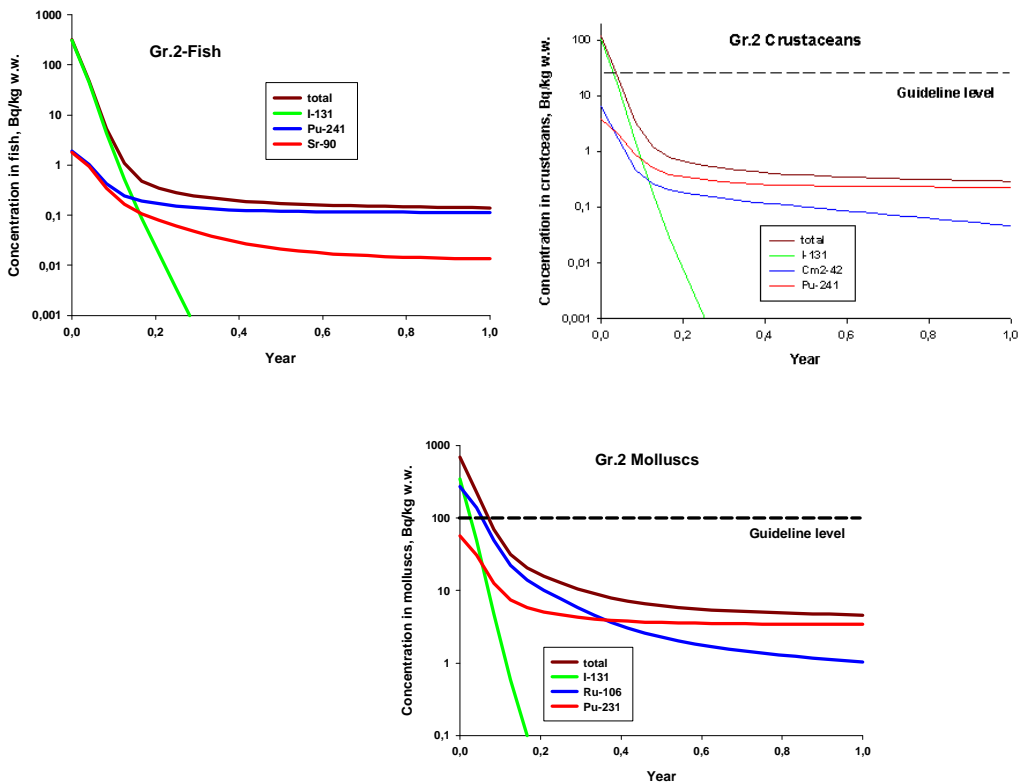


Fig. 30. Concentration of radionuclides (Group 2) in seafood.

The predicted concentration of radionuclides in fish is lower than the CAC guideline level for group 2 radionuclides. Results of the simulations for crustaceans and molluscs indicate that the radionuclide concentrations in the zone of the accident exceeds the CAC guideline level for a period of approximately one to two months after the accident. The predicted maximum values of the radionuclide concentration in crustaceans and molluscs are around 120 and 700 Bq/kg, respectively. The radionuclides that impacted the concentration levels in seafood (for group 2) the most were ^{131}I , ^{241}Pu and ^{106}Ru .

The concentrations of group 3 radionuclides in seafood are shown in Figure 31.

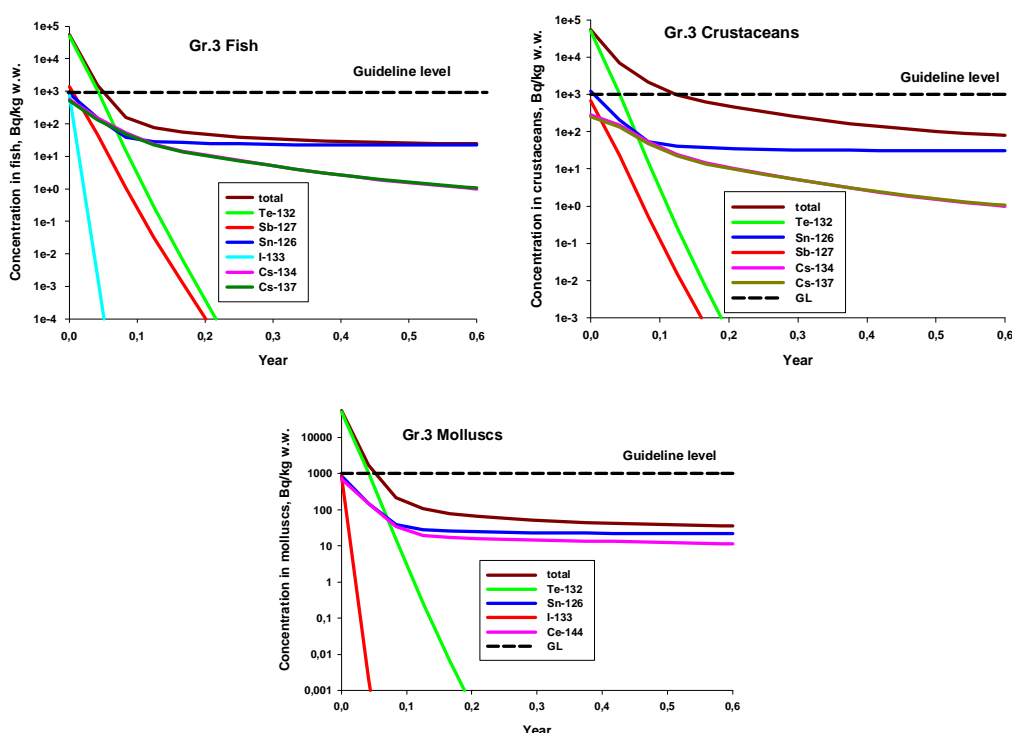


Fig. 31. Predicted concentration of radionuclides (Group 3) in seafood.

The results of the simulations for group 3 radionuclide concentrations in seafood indicate that the radionuclide concentrations in box 2 (the accident location) exceeds the CAC guideline value of 1000 Bq/kg for a period of approximately one-two weeks after the accident. The concentration of radionuclides is dominated by the level of ^{132}Te during these weeks. ^{126}Sn and ^{144}Ce (for molluscs) start to dominate the concentration level of group 3 radionuclides in seafood during the time following the two weeks after the accident.

Figure 32 shows that the contamination curves of seafood by group 4 radionuclides lies under the guideline levels for general food, but exceeds the guideline level for infant food for a period of approximately one week after the accident. ^{127}Te , $^{129\text{m}}\text{Te}$ dominate the radionuclide concentration during this initial time. During the time following this week,

^{125}Sb and ^{147}Pm have a significant impact on the total concentration of radionuclides in fish, and ^{103}Ru and ^{147}Pm dominate the radionuclide concentrations in crustacean and molluscs.

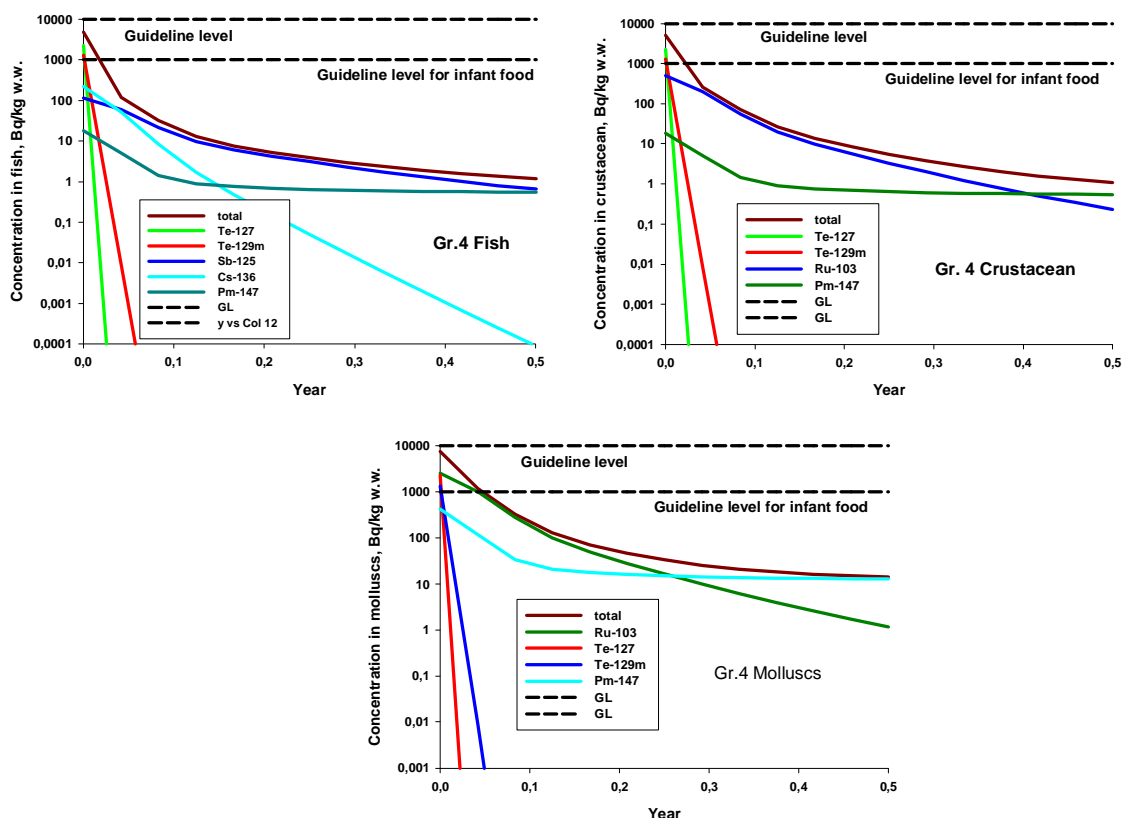


Fig. 32. Predicted concentration of radionuclides (group 4) in seafood.

Collective dose rates to man

The results presented in Figures 33 and 34 show that the maximum collective dose rates in the studied scenario, occur during the first year after the release of radioactivity. The maximum collective dose rate is approximately 58 manSv per year, with ^{134}Cs , ^{137}Cs and ^{126}Sn having the highest impact on the maximum collective dose rate.

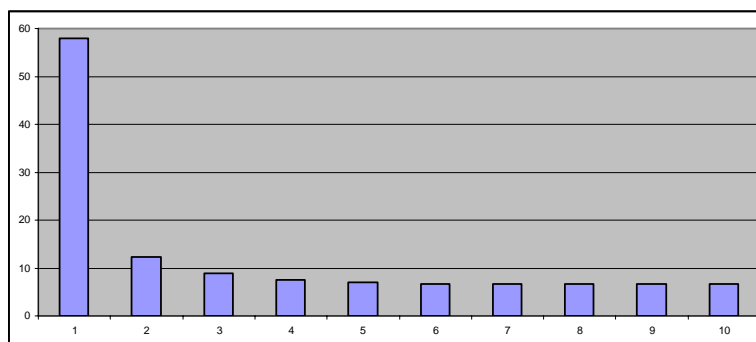


Fig. 33. Predicted collective dose-rates, manSv per year

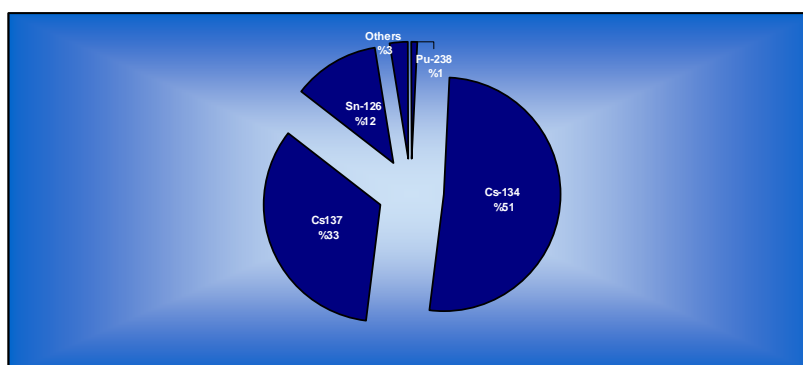


Fig. 34. Impact of radionuclides to the collective dose rate (the first year after the hypothetical accident)

Doses to the critical group

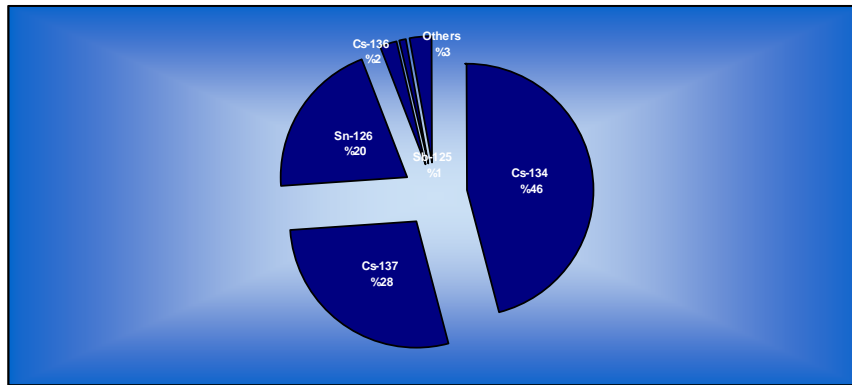
In the present study we assume that the critical group is a population living on the coast of the sea region nearest to the accident location. The evaluation of the doses for this group will be based on an investigation of consumption patterns for the population living on the Norwegian coast and inland (Bergsten, 2003), where maximum seafood consumption is 200, 40 and 4 g/day for fish, crustaceans and molluscs, respectively.

The individual dose rates for the ingestion pathway have been calculated on the basis of expressions (1) and (2), where catchments of seafood were replaced by consumptions for the critical groups.

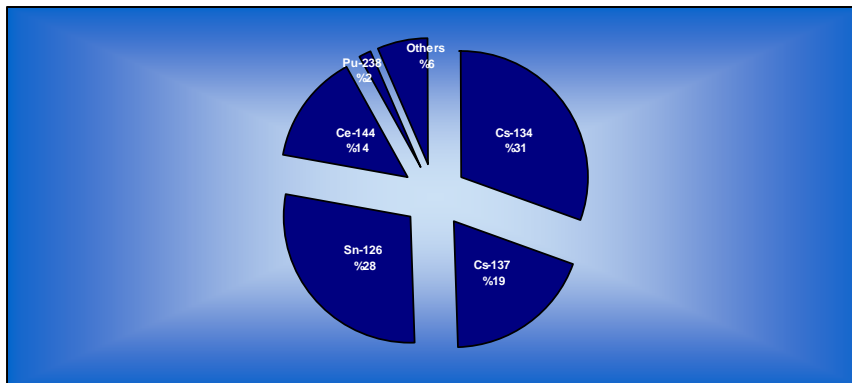
The proportions of the total calculated dose attributable to the different types of seafood are presented in Figure 35, corresponding to the maximum dose rate. Figure 35 shows that for the present scenario ^{134}Cs , ^{137}Cs and ^{126}Sn were the three radionuclides that gave the most significant contribution to the doses received from ingestion of seafood for the critical group. It is also necessary to note that the impact of ^{144}Ce is significant for the doses from crustaceans and molluscs.

The calculated maximum dose-rate equals $110 \mu\text{Sv yr}^{-1}$, which is significantly lower than the average annual dose of 1-10 mSv from nature sources. At the same time, this dose-

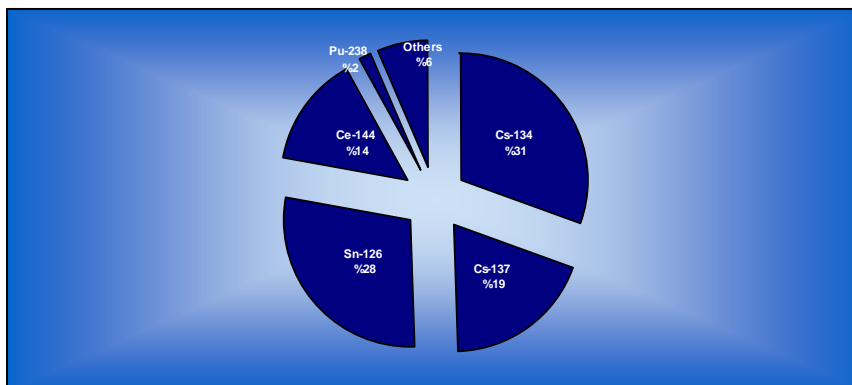
rate is significantly higher than range 1 - 10 $\mu\text{Sv yr}^{-1}$ for the negligible component to the annual individual dose from natural sources (UNSCEAR, 2000) and, therefore, has to be under consideration during evaluation of the accident consequences.



Fish (0.11 mSv per year)



Crustacean (0.02 mSv per year)



Molluscs (0.004 mSv per year)

Fig. 35. Potential dose impact to the critical group from fish, crustaceans and molluscs

Conclusions of submarine accident analysis

The consequences of an accident with a modern Russian submarine were calculated on the basis of the most conservative scenario from the ones were under consideration in the present investigation.

Calculations indicate that, generally, concentration of radionuclides in seafood would be under the international guideline levels for different groups of radionuclides. Simultaneously, results of calculations indicated that concentrations of radionuclides for some marine organisms during initial time of release near the accident location exceeded guideline levels. Elevated levels of radionuclides in marine food products may lead to economical consequences in a market very sensitive to contaminants, even if they don't exceed guideline levels.

Calculated collective dose rates to man as well as doses to a critical group are significantly lower than doses from natural sources, but at the same time, these dose-rates are significantly higher than the negligible component to the annual individual dose from natural sources (UNSCEAR, 2000) and, therefore, have to be taken into consideration during evaluation of the accident consequences.

References

Bergsten, C., 2005. Fish and Game Study, part B: "The consumption of foods that may be important when assessing the dietary intake of mercury, cadmium and PCB/dioxins, with a focus on population groups living on the coast and in the inland of Norway." Oslo: Norwegian Food Safety Authority, 2005.

CAC, 2006. Codex Alimentarius Commission: Joint FAO/WHO Food Standards Programme. Appendix 31. ftp://ftp.fao.org/codex/Alinorm06/al29_41e.pdf (09.01.07)

CEC, 1990. The radiological exposure of the population of the European community from radioactivity in North European marine waters. Project 'Marina', Commission of the European Communities. Bruxelles: EUR 12483.

EC, 2000. The radiological exposure of the population of the European Community to radioactivity in the Barents Sea. MARINA-Balt project. EC, Radiation Protection Series 110, EUR 19200 EN.

EC, 2003. Update of the MARINA Project on the radiological exposure of the European Community from radioactivity in North European marine waters. EC, Radiation Protection 132 Luxembourg, 2003.

IASAP, 2003. Modelling of the radiological impact of radioactive waste dumping in the Arctic Seas. IAEA-TECDOC-1330. Vienna: International Atomic Energy Agency, IAEA.

Iosjpe M., 2011. Radioecological sensitivity of the shallow marine environment. Radioprotection, 46, no 6, S189-S193.

Iosjpe, M., J. Brown & P. Strand, 2002. Modified approach for box modeling of radiological consequences from releases into marine environment, *Journal of Environmental Radioactivity* 2002, 60, 91– 103.

Iosjpe M. & Liland A., 2012. Evaluation of environmental sensitivity of the marine regions. *Journal of Environmental Radioactivity* 108 (2012) 2-8.

Iosjpe M., Perianez R, Aldridge J. & Børetzen P. (2003). Radionuclide dispersion models for Arctic, Atlantic and Mediterranean seas. Estimation of radiological sensitivity of marine areas. A deliverable report for REMOTRANS, Project FIGE-CT-2000-00085, December 2003.

Nielsen, S.P., Iosjpe, M. and Strand, P., 1997. Collective Doses to Man from Dumping of Radioactive Waste in the Arctic Seas. *The Science of the Total Environment*, 202, 135-147.

Petrov, E., 1991. Estimation of the Nuclear Power Plant Condition and Radiation and Ecological Consequences of a Prolonged Stay of the SSN 'Komsomolets' on the Sea Bed and During Its Recovery, (unpublished), submitted from the Russian Central Design Bureau Marine Engineering "Rubin" to the Norwegian Government, November 15, 1991.

UNSCEAR, 2000. Sources and effects of ionizing radiation. UNSCEAR 2000 Report to the General Assembly with Scientific Annexes. Volume I: Sources. UN, New York, 2000.

6 Conclusions

In the study consequences of severe radioactive releases to Nordic marine environment has been preliminary considered. The research activity has covered areas of Nordic marine input data, radioactive source term evaluations for nuclear power plants and for submarine vessels, marine flows and dilution aspects, element specific sorption and transfer factors and preliminary radiation dose estimates to human.

As a reference, the release amounts from a 3000 MW_{th} reactor size were used. Based on source term analyses, the chosen release fractions in the study were: iodine 20% (of the total core inventory), caesium 10%, tellurium 10%, strontium 0.5%, ruthenium 0.5%. The considered release event to marine environment were assumed to start ten hours after shutdown of the reactor. Total released amounts of the most important nuclides were estimated to be: $4.85 \cdot 10^{17}$ Bq (I-131), $7.29 \cdot 10^{16}$ Bq (Cs-134) and $4.17 \cdot 10^{16}$ Bq (Cs-137).

Due to the highly contaminated sea food, the arising doses to human would be high especially in local sea area. Based on preliminary results, annual individual doses could be ten to some hundreds of millisieverts from local sea area. The most important nuclides were Cs-134, Cs-137 and I-131 causing 96% of the total ingestion dose.

In the Baltic Sea area, the arising doses from a severe nuclear power plant accident assumed to happen at Gulf of Finland, would be about 1/10000 compared to doses in the local sea area. Thus the arising maximum annual individual dose for fish pathway is in the level of 0.1 mSv in the Baltic Sea area.

Submarine accident assumed to happen at Icelandic waters, has been analysed in the study. The calculated collective dose rates to man as well as doses to a critical group are significantly lower than doses from natural sources. However, in local considerations dose-rates are significantly higher than the negligible component to the annual individual dose obtained from natural sources (UNSCEAR, 2000) and, therefore, have to be taken into consideration during evaluation of the accident consequences.

In the planned continuing phase of the activity, more detailed marine 3D flow simulations will be done and utilized for Icelandic and the Faroese waters. Additionally, important model validation against measured data is necessary to carry out e.g. for the Baltic Sea region.

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Abstract	<p>In the report, consequences of hypothetical severe nuclear accidents releases to Nordic marine environment are preliminary considered. The considered marine area comprises the Baltic Sea (Sweden, Denmark, Finland) and the North Atlantic (Iceland, Faroes, Norway) areas. The hypothetical severe nuclear accidents can be related to nuclear power plants, nuclear powered submarines or ice-breakers.</p> <p>Quite comprehensive survey on radioactive source terms of extremely severe nuclear power and submarine accidents has been done. This enables to estimate more realistically possible radioactive releases of various elements and nuclides to marine environment. One recent reference is of course the Fukushima accident and estimated releases there.</p> <p>The marine flows and dilution circumstances around the Nordic nuclear power plants and in the Baltic Sea area in general, has been studied. Respectively marine flows related to Iceland and Faroes coasts are considered with measured data and with preliminary 3D-model simulations. The substantial depth of sea water in the North Atlantic affect vertical concentration profiles to some extent. At Icelandic or Faroese waters, a potential submarine accident would likely occur in a well defined water mass, and radioactivity from the accident would be detected and spread with the flow regime of the water mass in the world ocean.</p> <p>Based on hypothetical severe accidents scenarios, preliminary consequence calculations has been done. It should be emphasised that the considered severe accident cases, considered in this study, do not directly attach any</p>

specific Nordic nuclear power plant or any specific submarine type. The considered radioactive releases will, however, provide specified references for more extensive consideration of environmental consequences of severe - or minor - radioactive releases to Nordic marine environment.

As a reference, the release amounts from a 3000 MW_{th} reactor size were used. Based on source term analyses, the chosen release fractions in the study were: iodine 20% (of the total core inventory), caesium 10%, tellurium 10%, strontium 0.5%, ruthenium 0.5%. The considered release event to marine environment were assumed to start ten hours after shutdown of the reactor. Total released amounts of the most important nuclides were estimated to be: $4.85 \cdot 10^{17}$ Bq (I-131), $7.29 \cdot 10^{16}$ Bq (Cs-134) and $4.17 \cdot 10^{16}$ Bq (Cs-137).

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In the Baltic Sea area, the arising doses from a severe nuclear power plant accident assumed to happen e.g. at Gulf of Finland, would be about 1/10000 compared to doses in the local sea area. Thus the arising maximum annual individual dose for fish pathway is in the level of 0.1 mSv in the Baltic Sea area.

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Key words severe radioactive releases, marine environment, nuclear power plants, submarines, doses